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(MANTECH) PROGRAM

EVALUATION OF CAST TITANIUM ALLOY COMPRESSOR COMPONENTS - VOLUME I

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FINAL REPORT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this program was to characterize the properties of cast titanium alloy compressor impellers to provide a background for design, processing, and qualification for service in the Solar T62T-40 Titan auxiliary power unit and similar small radial gas turbine engines.

Four titanium alloy investment casting foundries participated in the production of straight vane test wheels, a low-cost representation of the
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compressor impellers. As-cast and hot isostatic pressed (HIPed) Ti-6Al-4V was seen to have less than half the high cycle fatigue strength (20 to 30 ksi versus 60 ksi) of equivalent sections from forged and machined impellers A modified solution heat treatment and aging cycle was developed which restored the fatigue strength to approximately 50 ksi, and which provided adequate tensile strength and ductility. High cycle fatigue strength of weld repaired vanes was significantly lower than that of unwelded, however.

One foundry, Precision Castparts Corporation, Portland, Oregon, was selected to produce prototype impellers and cast a total of eight wheels which were HIPed and heat treated according to the developed processes. Four wheels were finish machined and satisfactorily proof spin tested to 120 percent of engine speed (144% of operating stress). One wheel was burst spin tested to 106,000 rpm, 173 percent of engine speed (300% of operating stress) without failure. One additional wheel was installed in a test engine and has undergone over 200 hours service and 1124 start/stop cycles with 100 percent efficiency. Additional testing will be required to obtain full qualification of the wheel for engine operation.

Cast and machined wheels offer substantial cost savings over wheels conventionally machined from forgings. These savings may be as much as 50%, or about $900 per wheel.

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INTRODUCTION AND SUMMARY

The Solar Titan T62T-40 gas turbine auxiliary power unit is a high performance engine, widely used in DOD systems. The three major applications are the Army Blackhawk helicopter (UH-60A), the Air Force F-16 aircraft, and the Navy LAMPS helicopter. Total production requirements are expected to exceed 10,000 units over the next few years.

The engine employs a single stage, radial compressor impeller, approximately six inches in diameter. Engine speed is 61,248 rpm and the compression ratio 4.3/1. Early models of the engine employed a cast 17-4PH stainless steel compressor impeller, but upgrading to the present configuration required a change to Ti-6Al-4V, lowering weight and starting inertia. Manufacturing procedure for this impeller was by machining a 22 pound titanium alloy pancake forging to generate the 2.6 pound impeller, at a cost of approximately $2200 each.

This program was originated in May 1976 to investigate feasibility of producing the impeller as a near net shape by investment casting. The program was conducted in three phases:

1. Evaluation of foundry capability and casting properties in a low cost test piece simulating the compressor impeller.

2. Design and procurement of prototype impellers, based upon the characterization of cast titanium alloy.

3. Metallurgical evaluation, rig testing, and engine testing of the prototype impellers and definition of procurement and process control specifications.

1.1 PHASE I - EVALUATION OF STRAIGHT VANE WHEELS

The investment casting industry was surveyed for foundries experienced in casting of titanium alloys. Four foundries were contracted to cast 20 parts each of a simple straight vane wheel test shape. Based upon visual, mechanical and nondestructive evaluation tests of the castings, two foundries, Precision Castparts Corporation (PCC), Portland, Oregon and REM, Albany, Oregon were selected as producing acceptable quality parts. Evaluation of internal quality requirements of the impeller in dynamic service versus actual quality of the as-cast parts dictated that hot isostatic pressing (HIP) would be required to insure integrity of the

product. Fatigue tests conducted on blade sections of the straight vane wheels after simulated HIPing indicated that high cycle strength was less than half that of equivalently tested forged impeller blades. Metallographic examination of the microstructure indicated that a simulated HIP treatment, (without pressure) 1650°F/2 hr/slow furnace-cool, retains heavy grain boundary alpha phase. It was postulated that the high elastic modulus alpha acts as a stress concentration, initiating fracture in high cycle fatigue cycling. This mechanism of failure has also been proposed by D. Eylon, University of Cincinnati, "HCF Crack Initiation Analysis of Ti6Al4V Cast and HIP Specimens," Proceedings of the Net Shape Metal Working Program Review, December 1976, AFML-TR-77-51. Extensive thermal treatment studies were undertaken to effect a correction and it was determined that solution heat treatment by rapid cooling from a higher temperature, 1750°F, was effective in diminishing the dimensions of the grain boundary alpha. HCF limits were increased from approximately 30 to 50 ksi. It was determined that argon cooling from 1750°F was sufficiently rapid to confer these benefits, without introducing distortion problems from water quenching. Substitution of actual HIP cycles (with pressure) for the simulated, 1650°F/2 hr/furnace-cool, cycle in combination with solution heat treatment provided an almost equivalent benefit to HCF. The addition of a 950°F aging cycle, 4 hours, after solution heat treatment was seen to be effective in raising the yield strength and restoring the HCF limit to approximately 50 ksi.

Salt spray stress corrosion tests conducted on samples of the material in the preferred HIPed and heat treated condition disclosed the cast material to be equal to forgings in resistance. Erosion resistance of the casting was similarly equivalent to forgings in abrasive dust environment.

1.2 PHASE II - PROCUREMENT OF ROTOR CASTINGS

PCC was selected on the basis of quality and competitive bids to produce prototype quantities of the Titan impeller for test. The design was patterned after the machined forged impeller and does not compromise the efficiency of the compressor in any way. Production processes developed in the analyses of Phase I castings were codified as the process control specification (Appendix A), incorporating the developed HIP, heat treatment, and aging cycles. A total of eight castings were produced, four in each of two pours. These were HIPed, by Industrial Materials Technology (IMT), Woburn, Massachusetts, and subsequently heat treated and aged by Solar. The castings were evaluated by tensile tests of specimens trepanned from the bore of the first four; and by destructive metallographic, tensile and fatigue tests of one of the second lot (which was damaged in rough machining). Testing confirmed the expected benefits from the developed thermal treatments.

The mean yield strength, ultimate tensile strength, and elongation conformed to 120 ksi, 130 ksi, and 6 percent minimum requirements, respectively. However, there is some evidence that a portion of the population within three standard deviation limits will be below these values. High cycle fatigue life was similarly confirmed to be improved by solution heat treatment and aging, the limit being about 50 ksi in reversed bending stress.

1.3 PHASE III - QUALIFICATION TESTING

Four of the castings were finish machined, balanced, and proof spin tested at 73,500 rpm, 120 percent of engine operating speed, with negligible dimensional growth or distortion. One was spin tested to 106,000 rpm, or 173 percent overspeed and 300 percent overstress, and exhibited ductile growth only at the highest speeds of rotation and did not burst. Permanent diametral growth of approximately 1.0 percent was observed at the inner bore diameter, confirming stresses in excess of the material yield strength at the highest speeds. At 100 percent design speed the effective maximum stress on this diameter is approximately 70,000 psi. Obviously the plastic yielding was effective in relieving what otherwise would be 300 percent overstress at 106,000 rpm. Based upon these results, a second machined cast impeller was installed in an engine and has sustained over 200 hours operation and 1124 start/stop cycles without impairment and at full engine efficiency.

Cost of the cast impeller, including hot isostatic pressing, heat treatment, and machining is about 50% of the equivalent part machined from a forging. Savings per part is very much a function of production quantities, as is seen in Section 3, Economic Analysis.

Figure 1 is a photograph which summarized the major tasks of this program, illustrating the use of the straight vane wheel as a test vehicle. It is our belief that the processes developed for production of the Titan wheel are applicable to any radial impeller of comparable size. These data were presented to the DOD/MTAG Casting Technology Workshop in Arlington, Texas in March 1978, in hopes that progress can be made in reducing the cost of similar dynamic titanium parts.

The program was sponsored by the U.S. Army Aviation Research and Development Command and was monitored by the Army Materials and Mechanics Research Center, Watertown, Massachusetts. Mr. Frank Hodi was Technical Program Monitor.

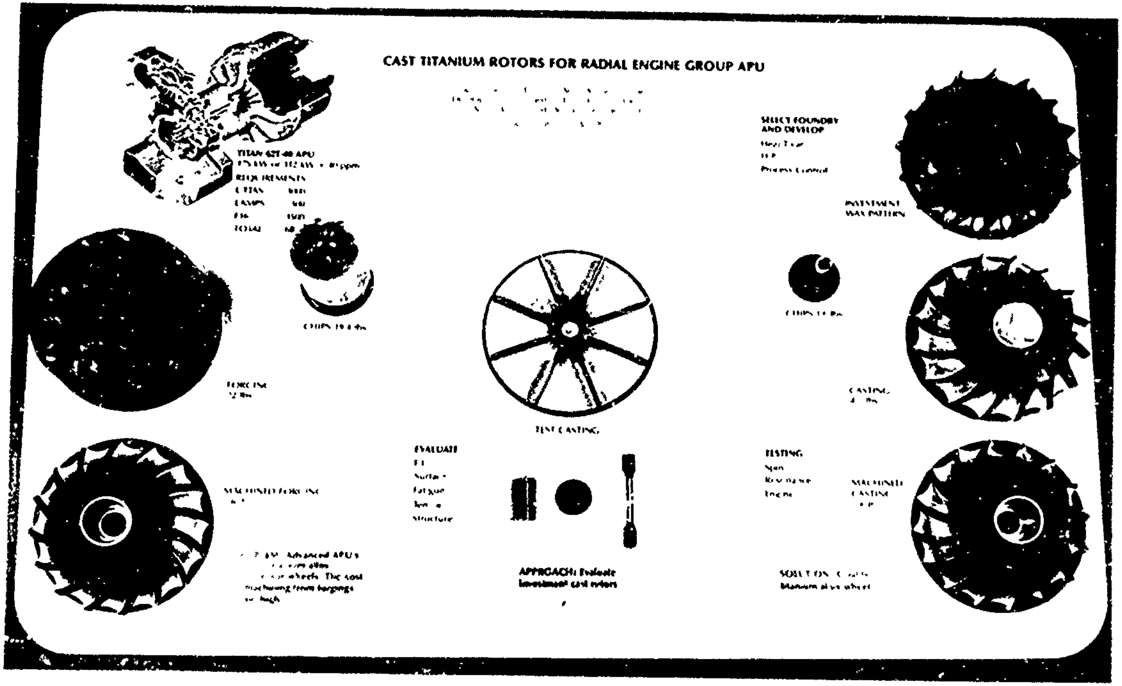

Figure 1. ⸱rogram Synopsis

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2

PROGRAM RESULTS

2.1 OBJECTIVES

The objective of this program was to demonstrate the suitability of cast titanium alloy for rotating compressor components prior to engine test. Properties of the cast alloy were characterized as they affect compressor design parameters, as a means of providing a background for qualification of the wheels for the Solar T62T-40 Titan and similar, small radial gas turbines. The program was conducted in three phases:

1. The evaluation of simple, straight vane wheel castings obtained from several foundries employing a variety of casting and post-casting processes;

2. Design of a production wheel based upon the evaluation of casting properties as influenced by the size, shape, and service environment; and

3. Simulated and actual engine tests of prototype wheels and the definition of procurement and process control specifications for production implementation.

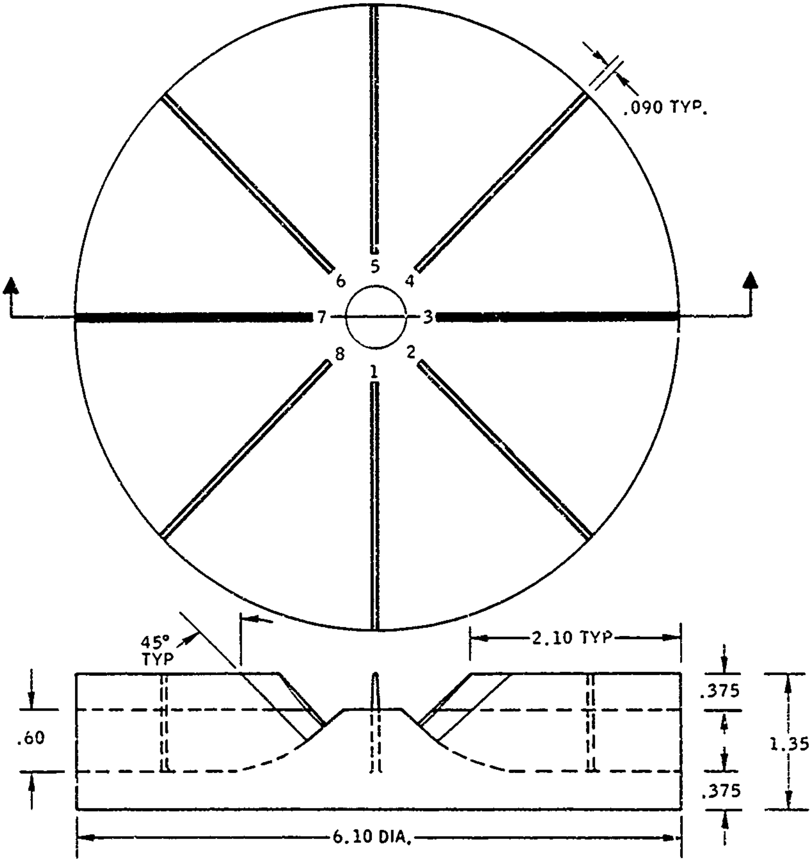
2.1.1 Phase I - Evaluation of Straight Vane Wheel Castings

Wax Pattern Procurement

A purchase order was let to TiTech International Inc., Pomona, California, for preparation of tooling to produce wax casting patterns shown in Figure 2.

Four foundries were contracted to produce the straight vane wheel castings from the TiTech wax patterns. The companies participating were:

TiTech International, Inc.	Pomona, California
REM Metals Corporation	Albany, Oregon
Howmet Corporation	Whitehall, Michigan
Precision Castparts Corporation	Portland, Oregon



VANES NO. 1 & NO.5 - LEADING EDGE .027" THICK
VANES NO. 2, NO. 3 & NO. 4 - LEADING EDGE .037" THICK
VANES NO. 6, NO. 7 & NO. 8 - LEADING EDGE .047" THICK
VARIABLE THICKNESS BLADES AT .375" FROM EDGE
VARIABLE FILLET RADII

Figure 2. Straight Vane Compressor Rotor Casting

Each foundry cast 20 parts. On the basis of discussions with the four foundries, it was decided that the first 10 castings would be produced using the best available standard techniques (as employed by that particular foundry). A review of these first ten castings was conducted at the foundry and the results used to dictate variations in techniques for production of the second ten.

REM Metals and Howmet waxes were produced in McCaughin* pattern wax; TiTech and Precision Castparts Corporation used Yates X71**. These particular choices are most compatible with the proprietary techniques used by the four foundries for mold preparation. Table 1 shows the variation in blade thickness of the two waxes and the conformance of the wax impression dies to the target dimensions of Figure 2. Figure 3 is a photograph of the typical wax pattern which was supplied to the participating foundries.

Casting Evaluation

Surface and Internal Quality - Visual examination and review of the first and second lots of ten castings from each foundry disclosed a variety of problems peculiar to the (proprietary) mold materials and techniques used. The results obtained, using straight vane wheels, are examples of the state-of-the-art early in the program at the time the castings were made, early 1979. The quality of the these castings should not be construed as representing in any way the current higher standards of all four foundries.

- Howmet - Poor surface quality; misruns, cold shuts, and porosity in blade-hub radii; lack of fill in most blade tips; internal quality approximately Grade D as related to Appendix A standards. (PCC Q.C.M. 9.1.7.1 - MIL-C-6021).

Table 1

Blade Edge Thickness, Mils, Wax Patterns

Thickness	Location*	Yates A71 Pattern Wax		McCaughn Pattern Wax	
		Mean	Std. Dev.	Mean	Std. Dev.
50	I	47.50	2.50	42.00	5.00
	M	50.00	0.00	45.00	2.00
	O	56.50	1.50	52.00	2.00
60	I	56.67	2.36	55.00	5.10
	M	60.00	4.08	55.00	4.08
	O	63.33	2.36	60.00	4.08
70	I	64.00	1.41	57.67	2.05
	M	66.00	1.41	61.33	1.89
	O	68.33	2.36	63.33	2.36

Notes: * I = Inside Diameter
M = Mid-length
O = Outside Diameter

*J.F. McCaughin Company, Rosemead, CA
**Yates Manufacturing Company, Chicago, IL

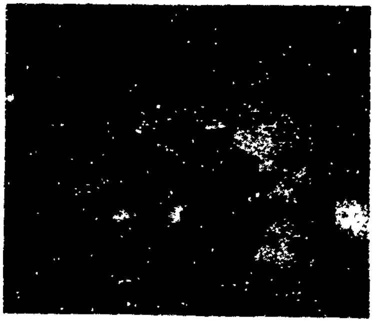


Figure 3.
Injection Molded Wax Pattern

- PCC - Large grain size (due to higher mold preheat temperature), 50 to 100 percent greater than castings of the other foundries, together with thicker alpha in the grain boundaries, as shown in Figure 4. Free of internal porosity, Grade A.

- REM - Uneven surface finish. Blade thickness 0.015 to 0.020 inch greater than target dimensions (Fig. 2), due to minimal chemical machining of the casting after mold removal. Good internal quality, Grade A.

- TiTech - Pin hole porosity on surface, thought to be related to metal-mold reaction. Internal quality was approximately Grade C.

Dimensional accuracy of the castings from three of the four foundries is shown in Table 2, a comparision of blade edge thickness to target dimensions of Figure 2. Lack of fill in the Howmet castings precluded measurement of the edge thickness. Measurements of thickness were taken at the tips of each blade at the outside diameter, mid-length, and near-center position. The result, reduced to mean and standard deviation values, show significant deviations from the target dimensions. The blades from all three foundries show a tendency to increase in thickness with increasing distance from the center which is the result of variations in the wax pattern. TiTech had the thinnest blade tips of any of the three foundries examined; and also the highest average standard deviations which relates to the extent of chemical etching conducted to reduce the blade thickness. Conversely, the REM blades were the thickest but had the best uniformity.

Chemical Composition

Table 3 is a compilation of chemical analyses on the straight vane wheel castings as determined by the foundries and by Solar. Except for slightly higher oxygen level in the TiTech product evaluated in two heats, no significant differences are noted.

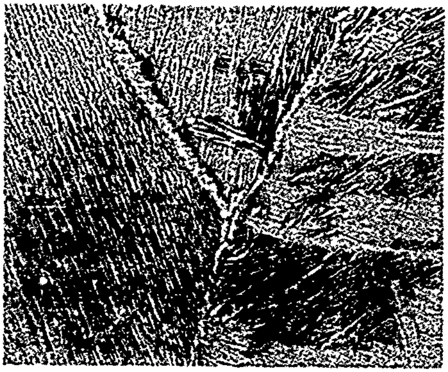


Figure 4.
Microstructure of PCC Casting
Magnification: 250X
Etchant: Kroll's
Log #2733

Table 2
Blade Edge Thickness, Mils, Castings

Thickness	Location*	Vendor					
		PCC		REM		TiTech	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
27	I	33.3	1.67	40.2	1.53	21.7	1.84
	M	34.4	2.67	40.4	1.74	25.2	1.06
	O	38.3	2.36	45.6	2.56	30.4	2.18
37	I	41.7	2.30	46.7	2.12	28.7	2.60
	M	42.6	2.31	47.4	1.94	32.0	2.49
	O	45.8	3.26	52.0	2.52	37.9	3.23
47	I	47.8	2.24	53.5	2.25	35.3	2.94
	M	49.0	2.90	54.5	2.38	38.7	3.25
	O	51.5	4.22	58.2	4.91	42.5	5.34
Total Blades							
Thin		16		20		19	
Medium		24		30		31	
Thick		24		30		28	

* Inside Diameter, Mid-Length, Outside Diameter

Table 3

Chemical Composition, Straight Vane Castings

Vendor	Heat Number	Composition by Weight Percent											
		Al	V	Sn	Fe	Zr	Mo	Y	O	N	H	C	
Howmet	TA-074 M/S	6 32	3 95	<0 02	0.18	<0 02	<0.02	<0.0015	0.185	0.014	0.0030	--	Vendor Analysis Solar Analysis
PCC	C2161	5 90 5 81	3.70 3 82	NR	0.17 0.13	NR	NR	0 0012	0.18 0.183	0 0067 0.0074	NR 0.00365	0.03	Vendor Analysis Solar Analysis
REM	930-D-6076	5 96 6.06	3 96 4 03	NR	0.202 0.17	NR	NR	NR	0.171	0.015	0.001	--	Vendor Analysis Solar Analysis
TiTech	3447	6.18 6.01	4 06 3.89	NR	0.17 0.13	NR	NR	NR	0 22 0.227	0.017 0 0162	0.0030 0.0127	-- --	Vendor Analysis Solar Analysis
TiTech	3584	6.10	4 06	NR	0.17	NR	NR	NR	0.22	0.014	0.0028	0 020	Vendor Analysis

Mechanical Properties

Tensile properties were determined on subsize specimens sectioned radially from the hub or vane areas of the straight vane wheel castings. Hub specimens had a nominal reduced gage length diameter of 1/8 inch. Vane specimens were flat coupons, the full thickness of the blades, 0.030 to 0.060 inch, and approximately 3/8 inch wide in the reduced gage section.

Fatigue tests were conducted on the blade-to-hub fillets by gripping a section of the hub and resonating the cantilevered blade vertically. A small weight was attached to the blade tip to intensify the stress. The blades were selected after careful examination of the radiographs and microscopic viewing of the fillets to represent, as nearly as possible, defect free material. Stress was measured on the surface with a strain gage at a location only about 1/16 inch removed from the fillet. The ratio of blade thickness to fillet radius is, for all blades tested, about 1/1 and the stress concentration at the point of failure, therefore, not very significant. Owing to the difficulty of sectioning tensile and fatigue specimens from the straight vane wheel castings while avoiding indications of defects, the test pieces were of several different configurations but generally conformed to the typical dimensions shown in Figure 5.

Thermal treatment, where applied, was accomplished either in vacuum, at 5 x 10^{-4} torr or better, or in an argon muffle box and the specimens subsequently chemically machined to avoid surface contamination.

It was recognized from a review of radiographs from the foundries and those made at Solar of selected parts, that the probability of detecting defects at the junction of the blade and hub was extremely poor, owing to reduced resolution at the abrupt change in dimension. The blade-hub radius location is believed to be critical to the performance of actual impeller castings in service due to: (1) to the tendency of shrinkage porosity to occur at the change of section thickness; and (2) the imposition of cyclic stresses on the

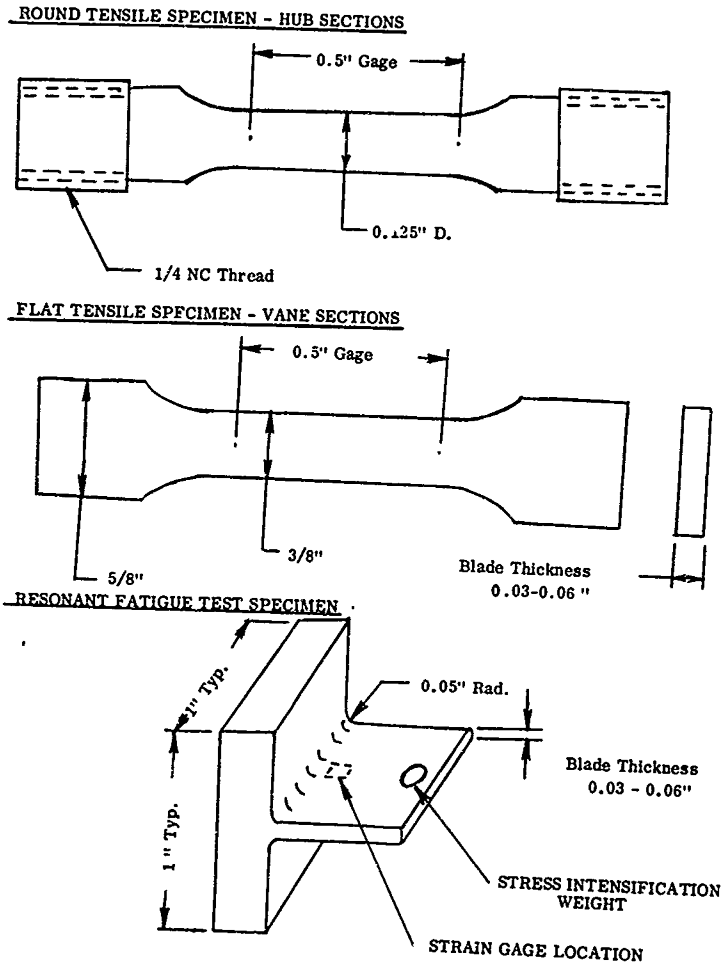


Figure 5. Typical Dimensions of Tensile and Fatigue Test Specimens Sectioned From Straight Vane Wheel Castings

radii in service condition transients, e.g., start-stop cycles. This combination of circumstances led to the requirement for Hot Isostatic Pressing (HIPing), of all castings intended for dynamic service.

In the initial stages of evaluation the specimens from straight vane wheel castings were subjected to simulated HIP cycles, i.e., comparable thermal treatment without imposition of pressure, to determine the effects upon microstructure, strength, and fatigue resistance. Tensile and fatigue properties of the initial evaluation are shown in Tables 4 and 5.

The results indicate that rapid cooling by argon or water from higher temperatures, 1750 or 1850°F, benefits high cycle fatigue (HCF) life more than does annealing (and slow cooling) at 1300 or 1650°F, treatments more representative of HIPing. Unlike the tensile specimens which appear to be adversely affected by internal porosity, the fatigue samples did not show this to be a problem, probably because the internal stress is low in flexural loading. In only a few cases, which are noted, did failure occur through obvious flaws, all surface defects, and located near the point of maximum stress.

Tensile and yield strength, in addition to HCF, are benefited by solution heat treatment and, further, by subsequent aging, at approximately 1000°F for 2 to 5 hours.

An evaluation was made as to the effect on tensile, yield strength, and high cycle fatigue life (of PCC castings) after a simulated higher temperature HIP cycle, 1750°F/2 hr/furnace cool, intended to eliminate either of the higher temperature heat treatments. The results, as shown in Table 6, indicate fatigue life of the castings is considerably less than forged baseline specimens.

Also evaluated were tensile properties of the hub section determined in this high temperature (simulated) HIP condition and in the (more conventional 1650°F) HIP simulated condition in combination with 1750°F heat treatment either before or after. Results of two specimens of PCC castings in each condition are shown in Table 7. Little difference is noted in the ultimate tensile strength, though all conditions fall short of the ASTM specification minima for castings. Elongations are similarly minimal, but some difference is noted in the yield strengths, with those of the dual heat treatment specimens significantly below that of the 1750°F simulated HIP samples. These data agree reasonably well with those determined earlier (Table 4) for hub specimens from PCC castings with simulated 1650°F HIP cycle. The material mill annealed (1350°F/2 hr/furnace cool) or solution heat treated (1750°F/1 hr/water quench) has significantly higher yield strength (and, in the case of SHT, higher tensile strength as well) with equivalent elongation. However, it is known from these previous data, that the high cycle fatigue strength is not benefitted by low temperature mill annealing, and the distortion problem inherent in water quenching were believed prohibitive for complex shapes. Therefore these two thermal treatments were excluded from further consideration.

After evaluation of two heats from each foundry, dimensional and visual analysis led us to narrow the candidates to two, PCC and REM. Howmet

Table 4

Tensile Properties, Straight Vane Castings

Company	Location	Condition**	0.2% Yield ksi	Ultimate ksi	R of A %	Elongation %	Notes
Howmet	Vane	As-cast	123.7	152.4	--	6.0	
	Vane	As-cast	121.6	142.5	--	?	BOGM*
	Vane	1650/2 Hr/FC/CH	?	132.7	--	?	BOGM
	Vane	1650/2 Hr/FC/CH	120.4	126.3	--	6.7	
PCC	Vane	As-cast	127.0	132.4	24.8	15.9	
	Vane	As-cast	122.4	133.9	20.8	9.6	
	Hub	As-case	115.0	130.5	20.0	10.0	
	Vane	Annealed 1300°F/2 Hr/FC/CH	--	131.6	--	8.7	
	Vane	Annealed 1300°F/2 Hr/FC/CH	118.8	132.6	--	10.9	
	Hub	Annealed 1300°F/2 Hr/FC/CH	119.2	131.6	--	5.1	
	Hub	Annealed 1300°F/2 Hr/FC/CH	118.3	132.4	--	9.3	
	Sep. Cst. Bar	Annealed 1300°F/2 Hr/FC/CH	123.7	134.0	16.2	7.1	Vendor Test
	Vane	Annealed 1650°F/2 Hr/FC/CH	96.8	125.2	--	8.0	
	Vane	Annealed 1650°F/2 Hr/FC/CH	99.4	124.3	--	8.0	
	Hub	Annealed 1650°F/2 Hr/FC/CH	119.5	126.2	--	8.0	
	Hub	Annealed 1650°F/2 Hr/FC/CH	110.3	122.2	--	8.6	
	Vane	1750/1 Hr/WQ/CH	123.6	160.7	--	6.7	
	Vane	1750/1 Hr/WQ/CH	146.3	150.8	--	2.7	
	Hub	1750/1 Hr/WQ/CH	131.9	131.9	--	4.0	
	Hub	1750/1 Hr/WQ/CH	144.5	151.5	--	7.3	
	Vane	1750/1 Hr/WQ/1000/5/CH	162.3	162.3	--	--	BOGM
	Vane	1750/1 Hr/WQ/1000/5/CH	152.0	167.5	--	5.3	
	Hub	1750/1 Hr/WQ/1000/5/CH	157.0	191.0	--	5.3	
	Hub	1750/1 Hr/WQ/1000/5/CH	--	82.1	--	--	BOGM
	Vane	1750/1/FC/CH	111.3	134.9	--	13.3	
	Vane	1750/2/FC/CH	104.8	127.7	--	13.3	
RMI	Vane	As-cast	117.7	133.1	10.2	6.8	
	Vane	As-cast	122.5	133.7	12.5	4.5	
	Hub	As-cast	125.1	137.3	11.0	5.9	
	Hub	As-cast	122.6	133.7	15.2	6.8	
	Vane	Annealed 1300°F/2 Hr/FC/CH	120.4	133.0	--	12	
	Vane	Annealed 1300°F/2 Hr/FC/CH	116.9	129.5	--	6.7	
	Hub	Annealed 1300°F/2 Hr/FC/CH	118.8	127.6	00	4.7	
	Hub	Annealed 1300°F/2 Hr/FC/CH	11[illegible].7	143.2	00	13.3	
	Sep. Cst. Bar	Annealed 1550°F/2 Hr/FC/CH	124.4	140.9	26.5	15.5	Vendor Test
	Sep. Cst. Bar	Annealed 1550°F/2 Hr/FC/CH	124.0	141.8	18.5	10.5	
	Vane	Annealed 1650°F/2 Hr/FC/CH	100.9	121.8	--	7.3	
	Vane	Annealed 1650°F/2 Hr/FC/CH	79.9	124.7	--	Nil	Broke through cold shut
	Hub	Annealed 1650°F/2 Hr/FC/CH	111.2	129.3	--	8.0	
	Hub	Annealed 1650°F/2 Hr/FC/CH	110.5	128.3	--	9.3	
	Vane	1750/1 Hr/WQ/CH	149.6	170.2	--	6.0	
	Vane	1750/1 Hr/WQ/CH	132.7	163.8	--	2.7	
	Hub	1750/1 Hr/WQ/CH	151.4	156.4	--	4.0	
	Hub	1750/1 Hr/WQ/CH	144.4	150.4	--	4.0	
	Vane	1750/1 Hr/WQ/1000/5/CH	138.9	145.7	--	--	BOGM
	Vane	1750/1 Hr/WQ/1000/5/CH	155.3	155.3	--	--	BOGM
	Hub	1750/1 Hr/WQ/1000/5/CH	154.2	154.2	--	0	
	Hub	1750/1 Hr/WQ/1000/5/CH	--	91.2	--	5.3	BOGM
	Vane	1750/2/FC/CH	111.9	129.3	--	13.3	
	Vane	1750/2/FC/CH	110.9	130.6	--	16.0	
TiTech	Vane	As-cast	137.8	149.4	17.1	11.8	
	Vane	As-cast	144.4	159.0	3.5	5.0	Broke through surface pits
	Hub	As-cast	133.2	149.3	13.2	8.7	
	Vane	Annealed 1300°F/2 Hr/FC/CH	130.2	141.7	--	5.8	
	Vane	Annealed 1300°F/2 Hr/FC/CH	111.1	155.8	--	6.5	
	Hub	Annealed 1300°F/2 Hr/FC/CH	131.4	145.5	--	6.2	
	Hub	Annealed 1300°F/2 Hr/FC/CH	126.8	143.8	--	6.2	
	Sep. Cst. Bar	Annealed 1325°F/2 Hr/FC/CH	131.4	154.2	17.8	7.0	Vendor Test
	Vane	Annealed 1650°F/2 Hr/FC/CH	99.6	137.7	--	4.0	
	Vane	Annealed 1650°F/2 Hr/FC/CH	116.7	129.9	--	5.3	
	Hub	Annealed 1650°F/2 Hr/FC/CH	117.1	131.7	--	6.6	
	Hub	Annealed 1650°F/2 Hr/FC/CH	121.8	130.4	--	6.6	
	Vane	1750/1 Hr/WQ/CH	--	122.9	--	4.0	BOGM
	Vane	1750/1 Hr/WQ/CH	131.6	145.1	--	9.3	
	Hub	1750/1 Hr/WQ/CH	104.5	139.4	--	4.0	
	Hub	1750/1 Hr/WQ/CH	118.2	124.4	--	4.0	
	Vane	1750/1 Hr/WQ/1000/5/CH	104.0	128.1	--	2.7	
	Vane	1750/1 Hr/WQ/1000/5/CH	157.4	174.9	--	2.7	
	Hub	1750/1 Hr/WQ/1000/5/CH	157.2	157.2	--	6.7	BOGM
	Hub	1750/1 Hr/WQ/1000/5/CH	103.0	123.4	--	8.0	
	Vane	1750/2/FC/CH	115.5	135.6	--	1.3	BOGM
	Vane	1750/2/FC/CH	123.3	151.7	--	4.0	
	Sep. Cst. Bar	1750/2/FC/CH	133.3	151.9	22.4	10	Vendor Test

*BOGM = Broke Outside Gage Mark
**Code = See Table 5

Table 5

Fatigue Properties, Straight Vane Castings

Vendor	Condition	Stress (ksi)	Resonant Frequency Hz	Cycles to Failure x 10^6	Comments
PCC	As Cast As Cast	30 40	2220 832	28 10 0.15	No Failure
REM	As Cast	30	2541	1 90	
TiTech	As Cast	30 40	1794 748	3.26 5.66	
PCC	1300F/FC/2	~20*	815	0.10	
REM	1300F/FC/2	30	2724	1.36	
TiTech	1300F/FC/2	~20*	722	0.09	
PCC	1650F/FC/2	30	1980	0 42	
REM	1650F/FC/2	30	2625	0.42	
TiTech	1650F/FC/2	30	1560	0.61	
PCC	1750F/1/WQ	30	1832	14.29	No Failure
REM	1750F/1/WQ	30	2123	15.92	No Failure
TiTech	1750F/1/WQ	30 30	1457 1650	0.56 0 73	Surface Porosity Surface Porosity
PCC	1750F/1/WQ 1000F/5/AC	30	2160	12.96	No Failure
REM	1000F/5/AC	30	2265	14.37	No Failure
TiTech	1000F/5/AC	30	1516	3.57	
PCC	As Cast	30	2087	0.69	
REM	As Cast	30	2565	0 84	
TiTech	As Cast	30	1391	12.71	No Failure
PCC	As Cast Glass Bead Blasted	30	2464	0.91	
REM	As Cast Glass Bead Blasted	30	2493	3.43	
TiTech	As Cast Glass Bead Blasted	30	1578	15 24	No Failure
TiTech	1750/2/FC	30	1463	4.40	
REM	1750/2/FC	30	2163	1 16	
PCC	1750/2/FC	30	1871	4.54	Cracked in vane at attachment point of weight
PCC	1750/2/FC	30	2033	1.45	
REM	1750/2/FC	30	2043	0.77	Cracked in pinhole in radius
TiTech	1300/ 2/FC	30	1687	12.14	No Failure
REM	1300/2/FC	30	2570	1.62	
PCC	1300/2/FC	30	2065	12.02	No Failure
Howmet	1300/2/FC	30	1960	1.88	
Howmet	As Cast	30	2079	12.47	No Failure
Howmet	1650/2/FC	30	2061	0.78	
Howmet	1750/2/WQ/1000/2	30	1334	12.01	No Failure
PCC	1650/2/FC/BB	30	2230	12.44	No Failure
TiTech	1850/1/FC/BB	30	1245	7.54	Cracked at pinhole in radius
Howmet	1850/1/FC/BB	30	1764	12.07	No Failure
REM	1850/1/FC/BB	30	1683	12 12	No Failure
TiTech	1750/1/AC/1000/5/AC/BB	30	1380	12.01	No Failure
REM	1750/1/AC/1000/5/AC/BB	30	2075	12.08	No Failure
Howmet	1750/1/AC/1000/5/AC/BB	30	1790	12.38	No Failure
PCC	1750/1/AC/1000/5/AC/BB	30	1961	12.35	No Failure

*Code: 1750/ = Temperature °F WQ = Water quench
/1/ = Time in hours CM = Chemical Mill, 0.005 in./surface
AC = Argon Cool BB = Glass Bead Blast
FC = Furnace cool

Table 6

Effect of Simulated Thermal HIP Cycle* on Fatigue Properties

Specimen I.D.	Stress ±, ksi	Frequency Hz.	Cycles to Failure x 10^6
PCC, 1-8, V6	40	2185	0.26
PCC, 1-11, V7	40	1855	3.70
PCC, 1-8, V8	50	2050	0.14
PCC, 1-11, V4	50	2142	0.18
PCC, 1-11, V3	60	2033	0.36
PCC, 1-8, V5	60	2133	0.22
PCC, 1-8, V7	70	1870	0.17
PCC, 1-11, V2	70	2221	0.33

Table 7

Effect of Simulated Thermal HIP Cycle* on Tensile Properties

Specimen I.D. (Nominal Size: .15 x .25 In.)	Heat Treatment °F/Hr/Cooling	Ultimate ksi	Yield ksi	Elongation % in 0.5 In.
PCC 1-3	1750/2/Furnace	125.9	117.9	9.5
PCC 1-3	1750/2/Furnace	121.2	111.7	6.1
PCC 1-8	1650/2/Furnace/1750/2/Air	124.1	107.9	6.1
PCC 1-8	1650/2/Furnace/1750/2/Air	127.1	107.5	5.3
PCC 1-8	1750/2/Air/1650/2/Furnace	119.1	100.0	6.7
PCC 1-8	1750/2/Air/1650/2/Furnace	123.8	109.0	6.7
Minimum per ASTM B367	Not specified	130.0	120.0	6.0

* Without pressurization

castings characteristically had many unfilled blade areas and cold shuts; TiTech appeared to have a problem with mold-metal reaction and consequent surface porosity. Table 8 is a compilation of fatigue properties of a baseline forged impeller and straight vane wheel castings produced by REM and PCC.

Two heat treated conditions were evaluated: 1650°F/2 hr/furnace cool/ 1750°F/1 hr/air cool; and the same in reverse order, i.e., 1750°F/1 hr/air cool/1650°F/2 hr/furnace cool. Both were followed by chemical machining of 0.002 to 0.003 inch from all surfaces in an $HF-HNO_3$ solution, and glass bead peening per AMS 2430, Almen Intensity 0.010-0.012 N, using size AB shot and pressure not exceeding 70 psig. The 1650°F portion of the treatment simulates thermal effect of the conventional HIP processing which, in previous tests, we had determined to have a negative influence on HCF life. The combination of the heat treatment at 1750°F followed by air cool, with the simulated 1650°F HIP, significantly improved HCF life, however, as shown in the results of Table 8. The properties are not significantly different whether the 1750°F is added before or after the 1650°F treatment and no differences could be noted in the microstructure. Both the PCC and REM castings reacted similarly, though the former has a grain size which is larger by about 50 percent. The HCF properties are comparable for either candidate foundry.

Fatigue results are plotted in Figures 6 through 9. Figure 6 shows the results on specimens sectioned from a production wheel machined from a forging. These specimens were mill annealed, 1350°F for 2 hours, furnace cooled, chem milled to remove surface effects, and blass bead blasted. With two exceptions* at 50 ksi stress level, all tests at 60 ksi or less alternating stress ran out to about 12×10^6 cycles without failure. The fatigue limit at 70 ksi stress level was about 2×10^6 cycles.

Figure 7 is a compilation of the results of several heat treatments evaluated on the REM (R) and PCC (P) casting samples. Again, all specimens except those in the as-cast (C) condition were chem-milled (CM) and bead blasted (BB) after the designated heat treatment. While some of each heat treat catagory may have run out, to 10^7 cycles, this was achieved consistently only with those specimens which had received heat treatments coded as F, S, or SA which require water quenching (WQ) or air cooling (AC) from 1750°F or above. One as-cast PCC specimen and one each PCC and REM beta annealed specimen also attained 10^7 or greater cycles at 30 ksi alternating stress. The standard HIP cycle, 1650°F for 2 hours and furnace cooled, designated as H, achieved only about 5×10^5 cycles at 30 ksi stress level. Mill annealed samples, designated as 3, had similarly reduced fatigue life.

Figures 8 and 9 are compilations of properties developed by PCC and REM castings, respectively, after a simulated HIP (1650°F/2 hr/furnace cool)

* For purposes of this discussion, specimen failure at the edges of the cantilevered blades are discounted as being influenced by stress raisers not representative of the true stress conditions.

Table 8

Fatigue Properties, Heat Treatment, and Simulated HIP Thermal Cycle

Vendor	Heat Treatment**	Stress ksi	Hz Cycles/ Second	Time Min.	Cycles $\times 10^6$	Failure Notes
Forging	3	30	1152	116.0	8.02	Blade Edge
Forging	3	30	1233	123.0	9.10	Blade Edge
Forging	3	30	1422	355.0	30.29	NF
Forging	3	30	1333	390.0	31.19	NF
Forging	3	30	1442	145.0	12.55	NF
Forging	3	40	2531	80.0	12.15	NF
Forging	3	40	1389	145.0	12.08	NF
Forging	3	50	1402	10.0	0.84	Root
Forging	3	50	745	167.0	7.44	Root
Forging	3	50	1081	190.0	12.32	NF
Forging	3	50	923	40.0	2.22	Edge
Forging	3	60	1715	120.6	12.41	NF
Forging	3	60	1130	180.1	12.21	NF
Forging	3	70	1282	20.0	1.54	Blade Edge
Forging	3	70	1750	3.8	0.40	Blade Edge
Forging	3	70	~1500	~14.4	1.30	Root
Forging	3	70	~1500	~21.7	1.95	Root
PCC	7	30	2176	95.0	12.40	NF
PCC	6	30	2030	100.3	12.22	NF
PCC	7	40	1807	115.0	12.47	NF
PCC	7	40	1983	105.0	12.49	NF
PCC	6	40	1755	115.0	12.11	NF
PCC	6	40	2061	100.0	12.37	NF
PCC	7	50	1790	10.4	1.11	Root
PCC	7	50	2050	100.0	12.30	NF
PCC	6	50	2070	14.1	1.75	Cold Shut
PCC	6	50	1510	37.5	3.34	Root
PCC	7	60	1890	23.6	2.67	Root
PCC	6	60	2176	3.9	0.51	Root
PCC	7	70	~2000	~4.6	0.55	Root
PCC	6	70	~2000	~5.5	0.66	Root
REM	7	30	2373	85.6	12.18	NF
REM	6	30	1990	105.3	12.57	NF
REM	7	40	2248	100.3	13.53	NF
REM	7	40	2138	85.8	11.01	Root
REM	6	40	2053	54.5	6.72	Root
REM	6	40	1900	110.0	12.54	NF
REM	7	50	2020	20.2	1.21	Root
REM	7	50	2200	36.0	4.75	Root
REM	6	50	* 2270	6.0	0.82	Root
REM	6	50	2240	22.7	3.06	Root
REM	7	60	2000	19.0	2.28	Root
REM	6	60	2209	4.6	0.61	Root

* Effect of thermal cycle only, without pressurization, was studied.

** 3 - 1350°F/2 Hr/Furnace Cool/Chem Mill/Bead Blast

6 - 1650°F/2 Hr/Furnace Cool/1750°F/1 Hr/Air Cool/Chem Mill/Bead Blast

7 - 1750°F/1 Hr/Air Cool/1650°F/2 Hr/Furnace Cool/Chem Mill/Bead Blast

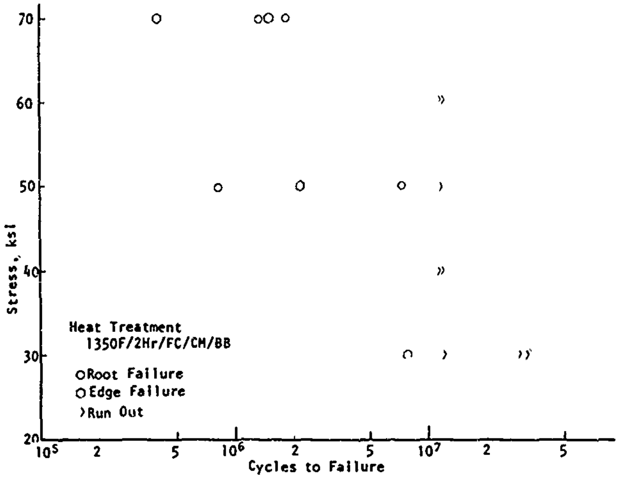


Figure 6. Blade Fatigue Life of Forged Rotors

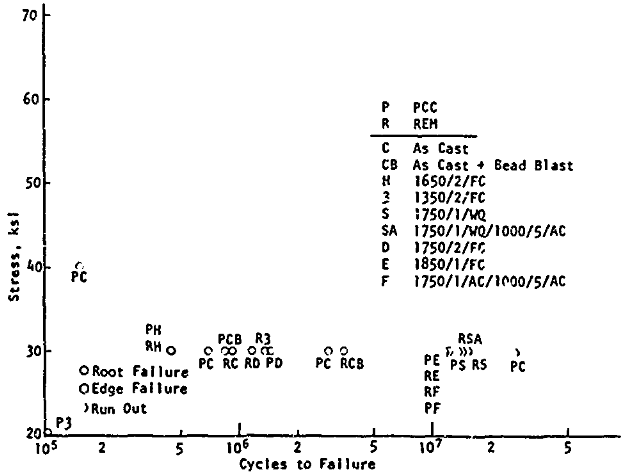


Figure 7. Blade Fatigue Life of Cast Rotors

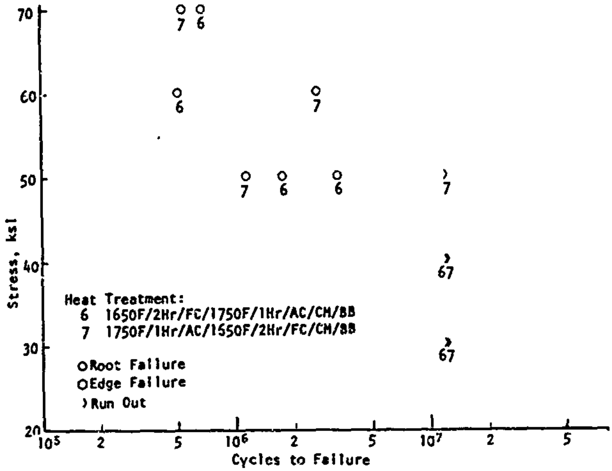


Figure 8. Blade Fatigue Life of PCC Cast Rotors With Simulated HIP-Solution Heat Treatment

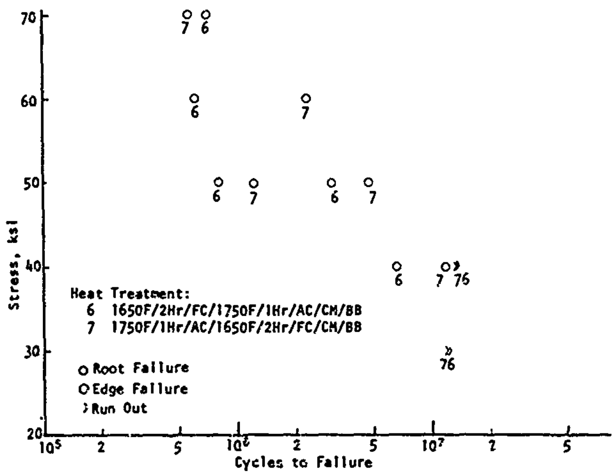


Figure 9. Blade Fatigue Life of REM Cast Rotors With Simulated HIP-Solution Heat Treatment

combined with a higher temperature, 1750°F/1 hr/air cool heat treatment. As can be seen from the data, the higher temperature heat treatment benefits fatigue life of castings from either foundry, whether conducted before or after the simulated HIP cycle.

Table 9 is a compilation of notched tensile data for the two combinations of 1650°F and 1750°F heat treatment as compared with a standard 1350°F mill anneal. Test specimens were prepared with a 0.252 inch major diameter, 0.160 inch minor diameter, 60 degree included notch angle, and 0.005 inch notch radius as shown in Figure 10. No significant differences are obvious and either combination of the higher temperature heat treatment shows satisfactory strength and ductility in triaxial stress loading.

HIPing and Heat Treatment

Ten castings were sent to Industrial Materials Technology (IMT) for HIPing at their facility in Woburn, Massachusetts. These represent several combinations of HIP, heat treatment, and simulated weld repair as shown in Table 10. IMT HIPed the castings in one load, after which they were returned to Solar for post heat treatment, where indicated, and testing.

Appendix A includes the IMT charts of load thermocouple locations, temperature and pressure profiles, and in process gas analysis. Note that cooling from the maximum temperatures of 1650°F to below 1200°F required about 70 minutes. We are advised by IMT that the gas analysis for this run is generally representative of an acceptable low level of interstitial contaminants. The parts themselves appeared unblemished except for the top two castings which showed irregular brownish smudges. No ready explanation is available, although IMT has suggested that material handling (probably at Solar) could be responsible.

Blade and hub thicknesses were measured before and after HIPing and no changes were noted either in dimension or in surface appearance of any of the castings.

Fatigue and tensile specimens were sectioned from the HIPed and heat treated castings. The vanes (fatigue specimens) were chemical machined to remove 0.002 inch from all surfaces and were glass bead blasted as previously described. Test results are shown in Tables 11 and 12.

Review of these data indicates no particular advantage in terms of strength or ductility for any of the evaluated heat treatments. The TiTech and Howmet castings appear to have some strength advantage, yield and ultimate, in all three of the heat treated conditions over REM and PCC. The latter two were selected earlier in the program as producing a sounder, better filled product, however. After the IMT HIP cycle, consistency of all results is improved over earlier tests of un-HIPed castings in similarly heat treated conditions, confirming the benefits of this treatment. None of these 22 specimens appeared to break prematurely through internal defects as was the

Table 9

Notched Tensile Data

Vendor	Heat Treatment*	Ultimate ksi	Yield ksi	Percent Elongation		
				1 In.	0.5 In.	0.25 In.
Howmet	7	195.0	186.9	1.4	3.1	6.2
Howmet	6	194.7	184.0	2.4	3.2	5.9
Howmet	3	195.2	193.2	1.1	2.2	3.7
PCC	7	189.4	180.6	1.6	3.2	5.3
PCC	6	218.8	186.1	1.4	2.7	4.5
PCC	3	185.1	182.7	1.2	2.3	5.1
REM	7	190.6	168.9	1.0	2.3	3.5
REM	6	194.5	186.6	1.1	3.3	5.7
REM	3	196.1	193.4	1.5	2.7	5.4

*3 - 1350°F/2 Hr/Furnace Cool/Chem Mill/Bead Blast

6 - 1650°F/2 Hr/Furnace Cool/1750°F/1 Hr/Air Cool/Chem Mill/Bead Blast

7 - 1750°F/1 Hr/Air Cool/1650°F/2 Hr/Furnace Cool/Chem Mill/Bead Blast

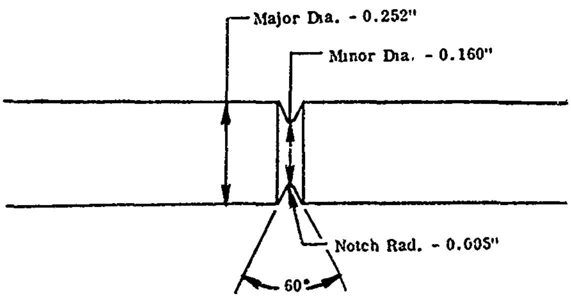


Figure 10. Notched Tensile Bar Specimen Dimensions

Table 10

HIP, Heat Treatment and Welding Schedule

Foundry	Casting I.D. No.	Preheat Treatment °F/Hr/Cooling	HIP Cycle °F/Hr/PSI/Cooling	Post Heat Treat °F/Hr/Cooling	Weld Blade No.
Howmet	6) TAO 76	1750/2/Argon	1650/2/15K/Furn	None	1,2,8
Howmet	4) TAO 76	None	1650/2/15K/Furn	1750/2/Argon	3,4,5
Howmet	7) TAO 76	None	1650/2/15K/Furn	None	None
PCC	1) 3A C2161-5 M1276-5	1750/2/Argon	1650/2/15K/Furn	None	1,6
PCC	5) 3A C2161-5 M1276-5	None	1650/2/15K/Furn	1750/2/Argon	3,5
REM	13) ML966	1750/2/Argon	1650/2/15K/Furn	None	3,4,5
REM	14) ML960	None	1650/2/15K/Furn	1750/2/Argon	4,5,6
REM	9) 6076	None	1650/2/15K/Furn	None	None
TiTech	3) 35434	1750/2/Argon	1650/2/15K/Furn	None	4,5,6
TiTech	2) 35434	None	1650/2/15K/Furn	1750/2/Argon	4,5,6
TiTech	8) -	None	1650/2/15K/Furn	None	None

case with several of the tensile specimens from un-HIPed castings. The maximum values of the HIPed material (including those that have been post-HIP heat treated) are less than those of sound, un-HIPed castings, however.

Seven blades were selected for simulated repair welding to evaluate the effect of this treatment on fatigue life. Areas approximately 1/8 inch long, 1/16 inch wide, and 0.01 to 0.02 inch deep were ground in the blade to root fillet, and were rewelded to simulate a repair according to the procedures specified in Appendix A, P.C.P. 59-001. The weld beads, where necessary, were polished to conform to the original cast shape. The specimens were not stress relieved, as specified by this process control procedure, but instead were HIPed and solution heat treated as noted in Table 10. The surfaces of both welded and unwelded specimens were subsequently chemical machined, 0.002 inch per surface, and glass bead blasted according to standard procedure. Fatigue test results, Table 11, are inconclusive as to loss in life of the welded versus unwelded specimens. These tests were preliminary and insufficient data are available to reach any definite conclusion.

Aging

The effect of aging on the fatigue strength of HIPed and heat treated castings is shown in Table 13. The REM castings have a higher fundamental resonance frequency than the PCC castings, reflecting the generally greater thickness of the blades.

Tensile and fatigue tests on the straight vane wheel castings confirmed the benefit of the 1750°F heat treatment followed by aging at 950°F. The compilation of fatigue data shows that, in comparison with properties reported in Table 14, strength has been improved by the 950 and 1350°F aging treatments in the case of the PCC casting. The REM castings did not respond as favorably to solution heat treatment and aging. Only one test ran out to 10^7 cycles at 40 ksi.

Table 11

Fatigue Properties, HIPed and Heat Treated Castings

Foundry	Casting	Blade No.	Heat† Treatment	Welded	Fatigue Results: Stress (ksi)	Hertz	Time Minutes	Cycles x 10^6	Notes*
REM	13	1	B	No	40 +50	2108 2079	79.0 6.8	10.0 0.85	NF F
REM	13	3	B	Yes	40	2028	23.3	2.8	F
REM	14	4	A	Yes	40 +50	2268 2260	74.0 3.4	10.0 0.46	NF F
REM	14	7	A	No	40	1835	39.0	4.3	F
REM	9	1	C	No	40	2397	18.0	2.6	F
PCC	1	1	B	Yes	40	2080	39.0	4.9	F
PCC	5	3	A	Yes	40	1941	12.3	1.4	F
Howmet	6	4	B	No	40 +50	1870 1865	90.0 1.68	10.0 0.18	NF F
Howmet	6	1	B	Yes	40 +50	1590 1582	105.0 13.1	10.0 1.2	NF F
Howmet	4	3	A	Yes	40 +50	1406 1406	119.3 18.04	10.0 1.52	NF F
Howmet	4	1	A	No	40 +50	1800 1795	92.3 22.9	10.0 2.47	NF F
Howmet	7	1	C	No	40 +50	1400 1380	120.0 38.2	10.0 3.16	NF F
TiTech	8	1	C	No	40 +50	1970 1965	84.0 60.0	10.0 7.1	NF F
TiTech	2	4	A	Yes	40	1492	65.8	5.9	F
TiTech	3	7	B	No	40 +50	1443 1429	115.8 55.5	10.0 4.7	NF F

*AC = Rapid Argon Cool
F = Failed
NF = No Failure

† A = HIP (IMT) 1650F/2Hr/15 ksi/Furnace Cool; Heat Treat (Solar) 1750F/2Hr/Rapid Argon Cool
B = Heat Treat (Solar) 1750F/2Hr/Rapid Argon Cool; HIP (IMT) 1650F/2Hr/15 ksi/Furnace Cool
C = HIP(IMT) 1650F/2Hr/15 ksi/Furnace Cool

Table 12

Tensile Properties, HIPed and Heat Treated Castings

Foundry	Casting No.	Heat Treatment†	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Reduction of Area (%)	Elongation % in 4D
TiTech	2	A	144.1 131.7	136.5 117.8	20.5 28.9	12.6 11.4
TiTech	3	B	139.4 137.1	127.8 126.3	38.9 20.4	14.6 10.3
TiTech	8	C	146.3 136.3	137.6 126.8	24.3 21.9	14.8 14.1
Rem	14	A	125.2 125.2	114.6 114.3	37.8 30.3	17.7 14.2
Rem	13	B	122.9 125.4	113.3 117.7	26.3 25.7	11.1 13.6
Rem	9	C	132.3 123.9	125.0 115.0	21.9 25.8	12.1 11.3
PCC	5	A	127.0 130.7	111.1 114.6	24.8 20.4	15.1 14.1
PCC	1	B	130.8 120.0	119.8 108.8	28.4 33.6	12.3 11.3
Howmet	6	B	133.0 134.6	125.2 125.6	11.0 9.3	23.3 15.8
Howmet	7	C	138.2 136.6	128.2 127.6	13.3 12.6	24.8 21.3
Howmet	4	A	137.2 137.0	126.1 125.7	10.7 12.4	18.9 24.7

* Subsize (0.125 in. dia). Specimens sectioned from casting hub, radial direction.

† A - HIP(IMT) 1650F/2Hr/15 ksi/Furnace Cool; Heat Treat (Solar) 1750F/2Hr/Rapid Argon Cool
B - Heat Treat (Solar) 1750F/2Hr/Rapid Argon Cool; HIP(IMT) 1650F/2Hr/15 ksi/Furnace Cool
C - HIP(IMT) 1650F/2Hr/15 ksi/Furnace Cool

Table 13

Effect of Aging on Fatigue Properties

Foundry	Casting No.	Blade No.	Heat Treatment*	Stress (ksi)	Hertz	Cycles x 10^6	Notes†
PCC	5	4	E	40	1960	10.1	NF
				50	1954	1.49	F
PCC	5	2	E	40	2043	13.85	NF
				50	2035	10.0	NF
				60	2020	0.58	F
PCC	1	7	F	40	1505	10.02	NF
				50	1500	10.0	NF
				60	1485	1.79	F
PCC	1	8	F	40	1760	10.02	NF
				50	1750	7.42	F
REM	14	1	E	40	2344	0.37	F
REM	14	2	E	40	2448	2.05	F
REM	9	3	D	40	2320	5.24	F
REM	9	4	D	40	2387	10.09	NF
				50	2354	0.58	F

*See Table 14
†No Failure; Failure

Table 14

Heat Treatment Schedule

Code	Thermal Cycle
A	HIP 1650F/2 Hr/15 ksi/Furnace Cool; Heat Treat 1750F/2 Hr/Rapid Argon Cool
B	Heat Treat 1750F/2 hr/Rapid Argon Cool; HIP 1650F/2 Hr/15 ksi/ Furnace Cool
C	HIP 1650F/2 Hr/15 ksi/Furnace Cool
D	Cycle C plus 1350F/4 Hr/Furnace Cool
E	Cycle A plus 950F/4 Hr/Furnace Cool
F	Cycle B plus 1350F/4 Hr/Furnace Cool

Table 15 presents tensile data on straight vane wheel castings from three foundries, and indicates in all cases an improvement in strength resulting from post-heat treatment aging at 950 and 1350°F as compared to unaged properties reported in Table 12. The combination of post-HIP heat treatment at 1750°F and subsequent aging, four hours at 950°F, produces the highest yield and ultimate strengths, and acceptable ductility.

2.1.2 Discussion - Heat Treating and HIPing

We have developed the following tentative explanations as to the effects on HCF of the several heat treated conditions.

The effective fatigue strength of the cast Ti-6Al-4V structure can be markedly influenced and sometimes improved by postcasting thermal treatment. A true analysis of the microstructural changes responsible for the noted improvement in fatigue strength (pre- or post-HIPing) is made difficult by the wide possible variety and complexity of structures formed during the $\beta \rightarrow \alpha$ matrix transformation. However, one reasonable analysis, which is correlatable with observed microstructural differences runs as follows:

1. The as-cast condition(s) (low fatigue strength) is characterized by large grain size and prolific, thick, continuous grain boundary (GB) alpha (see Fig. 4). This is typical of the heterogenous

Table 15

Effect of Aging on Tensile Properties

Foundry	Casting	Blade†	Heat Treatment*	0.2% Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation % in 4D	Reduction of Area (%)
REM	9	5	D	122.0	126.9	7.0	20.0
REM	14	7-1	E	125.9	134.0	10.0	16.1
REM	14	7-2	E	124.6	130.7	5.6	16.3
REM	13	1-1	F	120.7	125.7	6.2	19.8
REM	13	1-2	F	116.3	122.8	8.5	19.7
TiTech	2	7-1	E	133.6	146.7	10.8	24.5
TiTech	2	7-2	E	131.0	143.8	7.9	23.8
TiTech	3	4-1	F	126.8	133.7	8.9	19.3
TiTech	3	4-2	F	127.3	135.0	11.5	20.5
Howmet	6	4-1	F	123.0	130.6	9.6	21.3
Howmet	6	4-2	F	123.6	132.7	10.6	21.2
Howmet	4	3-1	E	126.7	137.2	13.3	27.5
Howmet	4	3-2	E	128.6	138.6	13.6	24.9

*See Table 14
†Sectioned from Base of Fatigue Specimen

α-nucleation and α-precipitation in slow-cooled segregation-prone Ti castings. Some investigators have argued that thick, long (high aspect ratio) GB alpha is potentially detrimental to fatigue, fracture toughness and other notch sensitive properties because such long grain boundaries are the structural elements most likely to fail first and form (long) continuous cracks (Griffith's Theory). This effect is accentuated by the higher elastic modulus of the alpha over the beta and transformed beta. Continuous cracking tendency at such as-cast grain boundaries is very likely promoted by the inevitable α-GB/stable β-phase boundary; the adjacent stable β deriving from the extensive impoverishment of α-stabilizing elements.

2. Post-cast solution annealing at 1650°F (simulated HIP) does nothing to improve the fatigue strength, inasmuch as this temperature is too low to dissolve significant GB-α; the 1650°F GB structure appearing essentially identical to the as-cast (Fig. 11). Additionally, the β in equilibrium with α at 1650°F is very stable, which situation retains the undesirable GBα/retained β phase boundaries.

3. Fortunately, solution annealing at 1750°F (or, more generally, between 1750°F and the limiting β transus of 1825°F) apparently acts to dissolve significant GB alpha, making it much less continuous and, where it (α) persists, appreciably thinner (Fig. 12). This is very desirable from a microstructural viewpoint.

   Equally important, the α-stabilizing elements are dispersed more uniformily throughout each grain, especially during long-term 1750°F treatment, so that upon rapid cooling, many stable internal α-nuclei are formed which favor more uniform, more homogeneous α-precipitation during any subsequent lower temperature holding. Logically then, this advantage will persist whether the 1750°F, rapid quench is applied <u>before</u> <u>or</u> <u>after</u> simulated HIPing procedure at 1650°F. Another potential advantage of 1750°F or higher pre- or post-HIPing treatment is that the less stable equivalent β which is formed at these higher solution temperatures tends to transform on cooling to alpha or alpha-related transition structure (α″). This more equivalent transformation produces a GB-α/α or GB-α/α′ known to favor higher fatigue endurance levels.

Although this analysis appears reasonable, the very large beta grain size and small total quantity of grain boundary alpha makes this hypothesis difficult to confirm. Also, in view of this factor, the location of the GB-α relative to the root radius surface will determine the effect on fatigue. It is again emphasized that the limited nature of the experiments and the considerable scatter of (even the best) fatigue data preclude more than a very elementary conjecture as to the true explanation of benefits conferred by heat treatment.

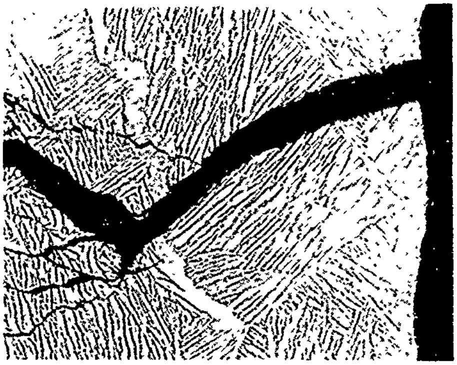


Figure 11.

Fatigue Crack Through Vane of Ti-6Al-4V Casting. Simulated HIP Condition, 1650F/2 Hr/FC

Magnification: 250X
Kroll's Etch
Log #5146

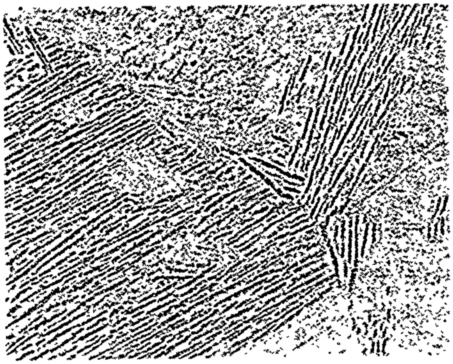


Figure 12.

Ti-6Al-4V Casting, Vane Section. Solution Heat Treated, 1750F/1 Hr

Magnification: 250X
Kroll's Etch
Log #2960

Corrosion Resistance

Salt spray testing of the HIPed and heat treated castings was conducted against baseline standards of the forging in the mill annealed condition. The salt spray specimens in the end restraint holders are shown in Figure 13. Each specimen was strain gaged on the reverse (compression) surface and strained with the moveable end screw to a maximum surface tension stress of 50 ksi. The specimens were checked periodically for signs of failure.

Five of the six stress-corrosion specimens sustained a total of 816 hours at 50 ksi maximum fiber stress: one cracked at 163 hours. Specimen identification is shown in Table 16.

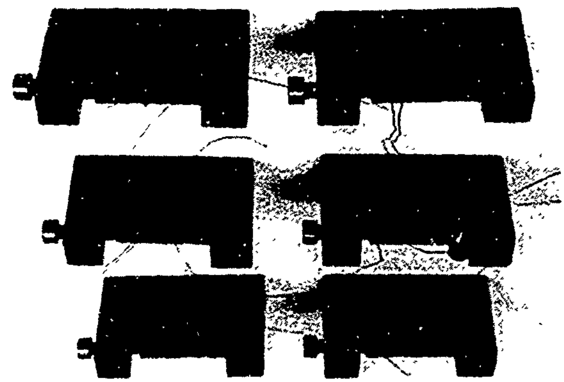


Figure 13. Salt Spray Stress Corrosion Test Specimens #78-5542

Table 16

Stress Corrosion Tests

Specimen No.	Foundry	Casting	First Exposure		Second Exposure	
			Heat Treatment*	Maximum Stress, 50 ksi Hours to Failure	Heat Treatment*	Maximum Stress, 70 ksi Hours to Failure
1	PCC	1	B	163	-	-
2	PCC	5	A	No Failure @ 816 Hr	E	No Failure @ 800 Hr
3	REM	13	B	No Failure @ 816 Hr	F	No Failure @ 800 Hr
4	REM	9	C	No Failure @ 816 Hr	C	No Failure @ 800 Hr
5	REM	14	A	No Failure @ 816 Hr	E	No Failure @ 800 Hr
6	Forging	-	1350F Mill Anneal	No Failure @ 816 Hr	Same	No Failure @ 800 Hr

*See Table 14

This first test was discontinued at 816 hours. Specimens 2, 3 and 5 were then aged four hours at 950°F, and all remaining five samples stressed to 70 ksi and resubjected to salt spray for an additional 800 hours. Again, no failures were noted in any of the specimens. It would appear from these limited data that the castings in the preferred 1750°F heat treated and aged condition are no more subject to stress corrosion cracking than are forgings.

Erosion Resistance

The dust erosion samples include one specimen each of a HIPed and heat treated cast blade, sheet stock, and a mill annealed forging plus one more of each which have been treated for improved surface hardness and erosion resistance. The latter was a proprietary Solar Solide™ coating which is produced by vapor phase reaction and diffusion. The resultant coating is a complex or single phase diboride, metallurgically bonded to the substrate.

Results, shown in Table 17, indicate no significant differences in the erosion resistance of the cast, sheet, or forged Ti6Al4V, and an equal degree of erosion resistance conferred to each by the Solide™ coating treatment.

Table 17

Erosion Test Results

Material	Weight Loss, mgms 43-74μ Arizona Road Dust 240 mps (783 fps) Particle Velocity
Sheet Stock	42.5
Forging	31.6
Casting	44.1
Solided™ Sheet	0.3*
Solided™ Forging	0.6*
Solided™ Casting	0.2*

*Isolated pits formed

2.2 PHASE II - PROTOTYPE PRODUCTION

2.2.1 Selection of Foundry and Tool Maker

Competitive quotes were sought from two foundries, PCC and REM, in May 1977 for production of prototype quantities of the Titan impeller castings, pre-release Drawing #160074, Appendix A. PCC was selected on the basis of these quotes and authorized to proceed with hard tooling. Richcraft Company of Los Angeles, California was contracted to produce the tooling. Figures 14A and 14B are photographs of the combination plastic/wax patterns which were produced.

2.2.2 General Foundry Production Method

Plastic-wax patterns are fabricated by injection molding in steel dies. These pie segments containing two blades, the full and splitter blades, are assembled together around the (wax) hub to form a total wheel. The wax shape which is slightly larger than the final casting size, compensating for metal shrinkage, is gated and the pattern tree coated with a series of proprietary dips to form a refractory mold. As the mold is fired the wax and plastic melt away, leaving a negative void in the shape of the impeller casting.

All four foundries currently engaged in investment casting skull melt a consumable titanium alloy electrode, in vacuum, dumping into the preheated mold directly from the water-cooled copper crucible. The degree of preheating of the mold, and its cooling characteristics have been seen to have a significant influence upon the properties of the casting. Hotter, slower cooling molds favor better flow and filling of thin passages but result in significantly larger grain size due to slower solidification.

The final step of the casting process is to break and wash away the refractory mold material, saw and snag the gates and risers from the castings, and conduct rudimentary machining to facilitate subsequent processing.

Following the steps required to produce the casting, many of which are proprietary within the casting industry, the part requires chemical machining of the blades which have been cast oversize to abet metal flow in casting. Preliminary nondestructive inspection is introduced to detect surface connected flaws prior to HIPing at 1650°F for 2 hours. The flaws are ground out, (within size limitations in critical areas) and weld repaired if allowed.

A second chemical machining is performed to remove interstitial surface contamination from HIPing after which partial solution treatment is performed. A third chemical machining further reduces blade thickness to final dimension. Subsequent aging in vacuum serves both to improve mechanical properties of the part, and to draw off some residual hydrogen introduced by the chemical machining steps.

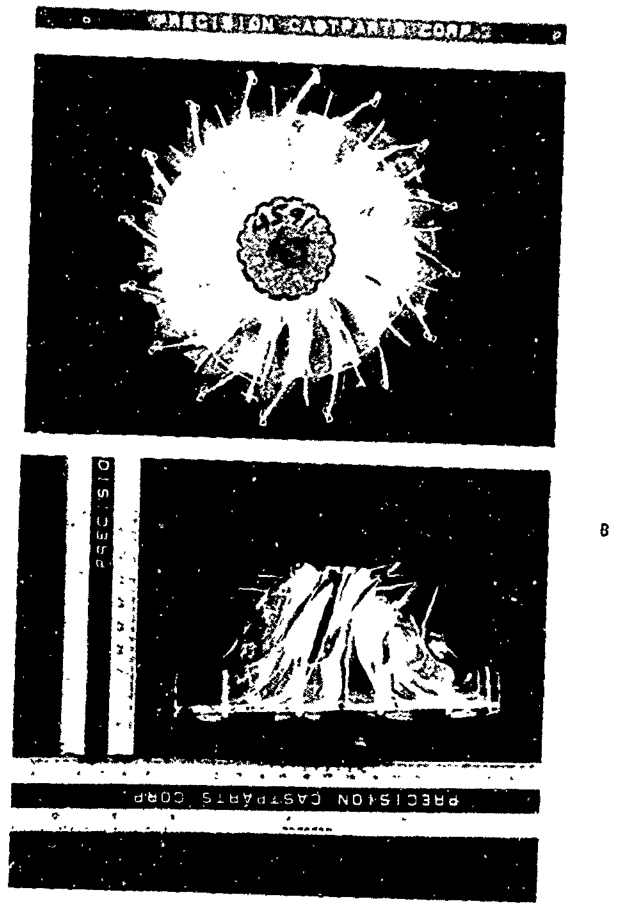


Figure 14. Injection Molded Plastic/Wax Patterns

Appendix A includes the PCC process control documents which are applicable.

Machining of the casting requires boring the center hole, reducing the thickness of the back face and trimming the length of the blades, all lathe turning operations which can be accomplished at no great cost. Tests (Phase I) show a significant improvement in endurance limit by glass bead peening of the hub-to-blade radii improving the finish and inducing compressive stresses at the surface. The finished part is balanced - to within 0.025 inch-ounces - and proof spin tested at 73,500 rpm for one minute, 120 percent of operating speed and 144 percent of operating stresses.

2.2.3 Prototype Production

A coordination meeting was held at PCC in Portland in anticipation of the first pour of prototype wheels. It was decided that only one of the first four castings (the one dimensionally worst) would be heat treated at Solar, at 1750°F, in view of our (and PCC's) limited experience with possible distortion of curved blades at this higher than usual temperature. Depending upon the outcome, the balance would be processed with the necessary fixturing either at PCC or at Solar.

A total of eight castings were poured and HIPed (by IMT) in two lots. Of these, the first four were dimensionally marginal due to inaccuracies in the plastic/wax patterns, since corrected. These four were heat treated at Solar in two lots. The first lot consisted of a single casting (S/N 1054-0002) which had half of the blades supported during the 1750°F, 2 hour, rapid argon cool cycle by alumina thermocouple beads, while the remaining blades were unsupported. Plaster patterns taken of the spaces between the blades showed negligible distortion of either half. The remaining three castings in the second lot were heat treated without support, all were chemical machined 0.002 inch per surface, and subsequently aged in vacuum for four hours at 950°F. These four castings were sent to a subcontractor for machining to final dimensions and balancing. Figure 15 is a photograph of a rough machined and finish machined casting showing the minimal dimensional changes necessary to prepare them for engine operation. The first batch of four had the blades embedded in a low melting alloy to restrain them during interrupted cutting of the outer diameter. The center cores were trepanned and used for tensile specimens.

The second lot of four castings also were HIPed at IMT and were heat treated by Solar.

2.3 PHASE III - EVALUATION

Table 18 is a compilation of tensile data determined: (1) from axial specimens trepanned from the bore of the four castings in the first pour; and (2) from specimens sectioned from the (machining) damaged casting of the second production pour. All of the castings were subjected to identical

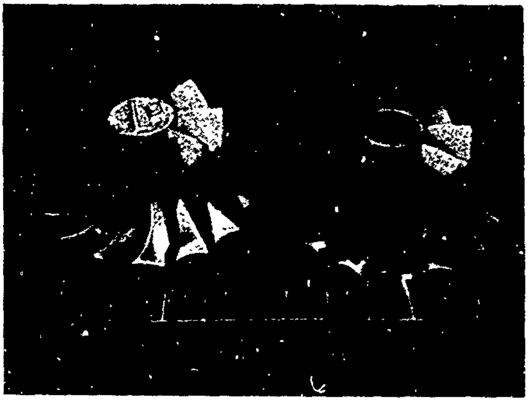


Figure 15.

As-Cast and Finished Machined Impeller #78-0260

Table 18

Tensile Properties, Prototype Castings

Casting Serial No.	Specimen	Ultimate Tensile (ksi)	0.2% Yield (ksi)	Elongation Percent % in 4D	Reduction of Area (%)
0000A	Axial, Hub	134.1	121.1	8.4	14.7
0002	Axial, Hub	130.5	118.1	8.5	14.6
0005	Axial, Hub	133.5	121.3	6.5	14.7
0008	Axial, Hub	134.3	120.9	7.5	11.0
0007	Axial, Hub	131.8	121.2	5.1	11.0
0007	Axial, Hub	131.7	120.2	7.0	12.0
0007	Radial, Hub	131.0	119.1	7.2	15.8
0007	Radial, Hub	130.2	121.1	6.0	14.6
Specification Minima		130.0	120.0	6.0	-
Mean Value		132.15	120.36	7.02	13.53
Sigma		1.62	1.17	1.16	1.91
3 Sigma Limits:					
Minimum		127.3	116.8	3.6	7.8
Maximum		137.0	123.9	10.5	19.3

HIPing, heat treatment, and aging cycles; and all were from the same lot of metal. Discounting differences in properties between axial and radial directions - which assumption seems valid based upon the results - the mean, standard deviation, and total (3 standard deviation) population have been calculated for each of the properties. These data are plotted as histograms in Figures 16 through 19, illustrating that while the mean and majority of results exceeded the specification minima, some portion of the population - particularly in the case of yield strength - may be expected to fall below this level. The disparity between the actual test results, shown as the histographic plots, and the normal bell curve distribution about the mean is also evident indicating the preliminary nature of these results.

Figure 20 is a copy of the Material Certification furnished with each lot of castings, delineating test results of Metal Lot #13520 as determined on separately cast test bars in the mill annealed (1300F/2 hr) condition. These properties are, it will be noted, somewhat higher than those of specimens from the HIPed, heat treated and aged castings.

Table 19 and Figure 21 show results of resonant fatigue tests performed on two blade-hub specimens sectioned from casting S/N 0007, damaged in machining These data coincide with those determined on similar specimens from the straight vane wheel castings and confirm the advantage of the selected HIPing, heat treating, and aging cycle which has been incorporated into the process specification, Appendix A.

Metallographic examination of casting S/N 0007 disclosed a relatively large grain size in all areas, particularly the hub. Figure 22 is a photomacrograph of a polished and etched cross section. Examination at higher magnification disclosed that primary alpha in grain boundaries was much less than had been seen in as-HIPed or annealed specimens, thereby substantiating the hypothesis relating improved high cycle fatigue life to the reduced thickness of grain boundary alpha.

The four HIPed, heat treated, and aged castings from the first foundry lot were machined to final part dimension, as shown in Appendix A, Process Control Specification and Engineering Drawing. Machining of the four castings from the second production lot is pending completion of engine tests of the first lot. Only one dimensional discrepancy is noted in inspection of the machined castings: the scallops at the outside diameter of the impeller are slightly displaced with respect to the location of the blades with the result that the extreme trailing edge of the blade has a different radius on opposite sides of the blade. It is impossible to say how much this change in radius will affect performance or life of the impeller in service, if at all. The inaccuracy can be corrected by tighter dimensioning on the engineering drawing, however it will be necessary to rebuild the assembly fixture for the plastic/wax patterns to the revised tolerances. Laser holographic analyses of the blades indicate the fundamental resonant frequency of the cast part to be consistently less than the forged part in bending of the leading and trailing edges. Results are shown in Table 20 and a typical example of the holographic patterns shown in Figures 23 and 24. Interference lines in the photographs correspond to a physical displacement of the blade amounting to approximately 11 micro inches per fringe. The difference in radii on opposite sides of the cast blades can be seen in Figure 24.

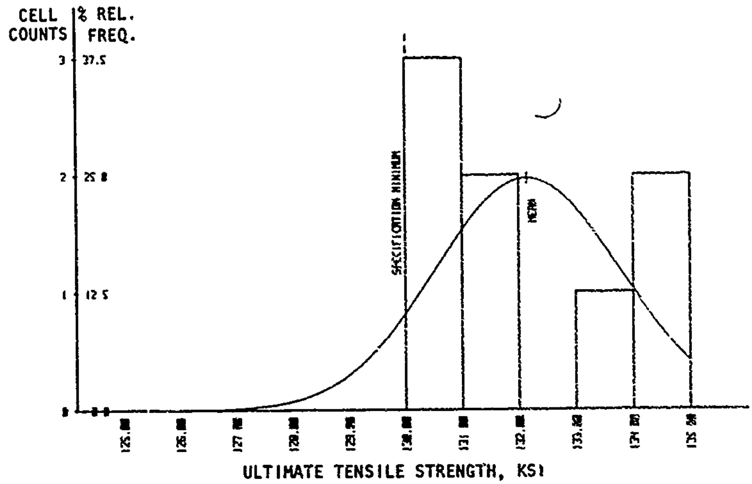


Figure 16. Histogram

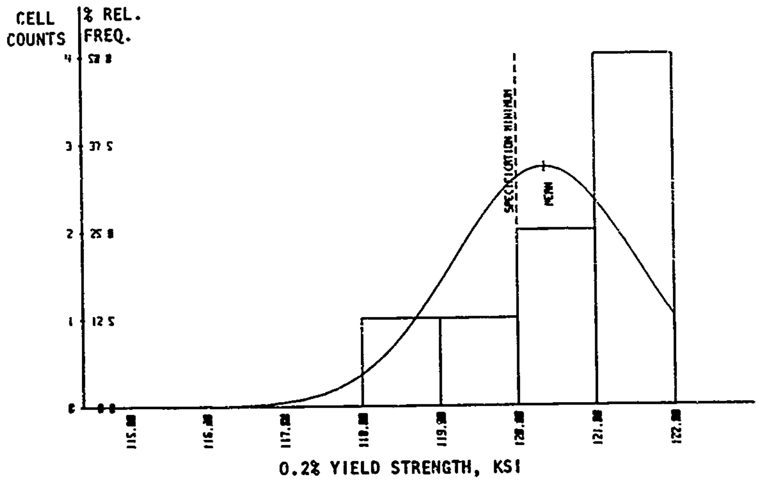


Figure 17. Histogram

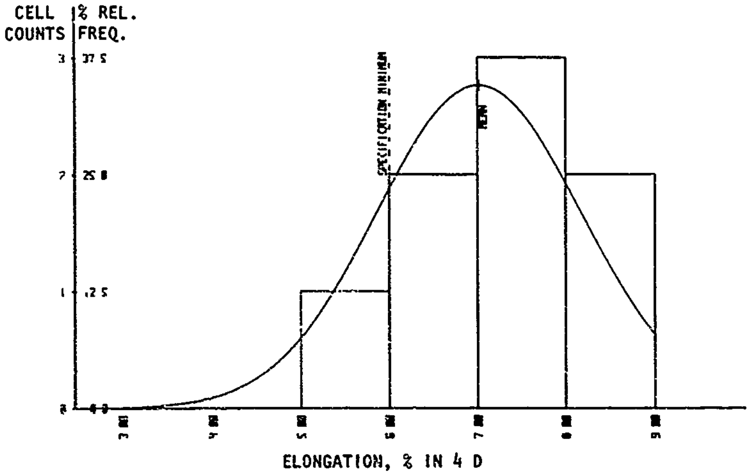


Figure 18. Histogram

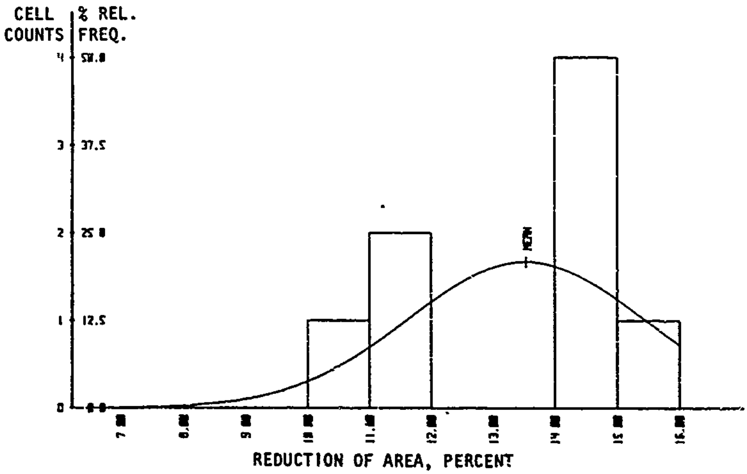


Figure 19. Histogram

Precision Castparts Corp.

4600 S.E. Harney Drive
Portland, Oregon
97206

Telephone (503) 777 3881
TWX 910 464-6130

Material Certification

Date 11-28-77

9010-b

ALLOY TYPE	METAL LOT NO	SPECIFICATION(S)
Ti 6-4	13520	ASTM B-367,Gr.C-5

RAW MATERIAL VENDOR	CUSTOMER NAME
R.M.I.	SOLAR DIVISION

CHEMICAL ANALYSIS

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe	Co	Cb
021									.18		
Al	**Ti**	**B**	**V**	**W**	**Zr**	**Sn**	**O_2**	**H_2**	**N_2**	**Y**	
5.95			3.90				.1650	.0046	.0071	ppm 35.0	

ROOM TEMPERATURE TENSILE PROPERTIES –

YIELD STRENGTH (PSI)	TENSILE STRENGTH (PSI)	ELONGATION (IN 4D) %	REDUCTION OF AREA %	HARDNESS
124,200	134,000	7.7	14.0	33 Rc

ELEVATED TEMPERATURE TENSILE PROPERTIES @ ______ °FAHRENHEIT

YIELD STRENGTH (PSI)	TENSILE STRENGTH (PSI)	ELONGATION (IN 4D) %	REDUCTION OF AREA %	HARDNESS
V-Notch				

STRESS RUPTURE @ RT °FAHRENHEIT AND 170,000 PSI STRESS

~~OK @ 5Hrs. Discontinued at 11.3 hrs.~~

RUPTURE LIFE (HOURS) ______ ELONGATION % ______ INCREMENTAL LOADING ______ TO ______ PSI @ ______ HRS

Comments and/or Attachments –

Chemical Analysis and R.T. Tensile Test performed by PCC.
O_2, N_2, H_2, V-Notch Stress Rupture Test performed by Koon.hall Testing Corp.
Yttrium Test performed by National Spectrographic Laboratories, Inc.

Heat Treatment for Test Material
Anneal : 1300°F for 2 hrs. in Argon, cool in Argon to below 1000°F.

P/S 103767

6156

4 pcs S/N NDT 00,02,05,08

This is to certify that material, parts or components of assemblies have been inspected to the specifications involved and results of tests required are as shown herein.

Precision Castparts Corp.

Authorized Signature [signature] Lab Supervisor

Figure 20. Foundry Material Certification

Table 19

Fatigue Properties, Prototype Castings

Specimen	Stress (ksi)	Resonant Frequency Hz	Cycles to Failure x 10^6	Comments
1	40	1190	10.0	No Failure
	50	1185	0.4	
2	50	3418	6.3	

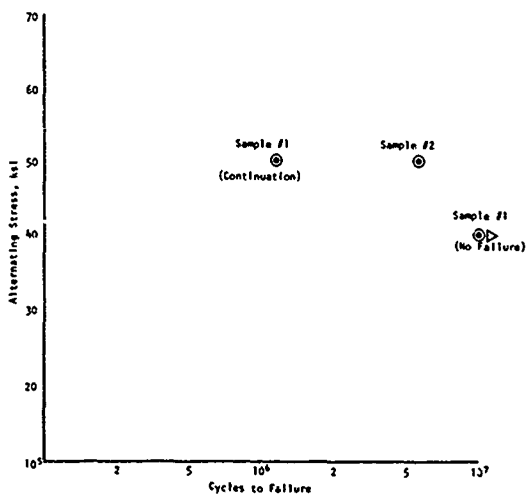


Figure 21. Blade Fatigue Life of Prototype Impeller

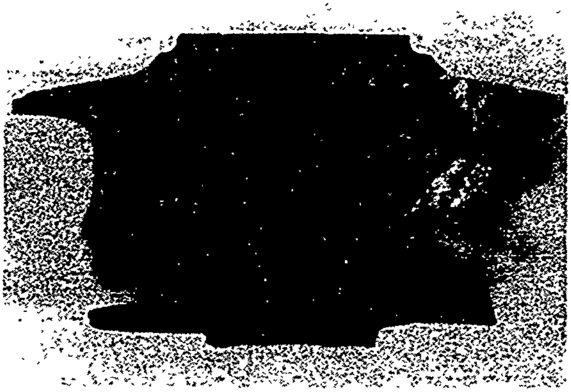


Figure 22. Casting Macrostructure (#78-1212)

Table 20

First Flap, Fundamental Frequency, Bending

Forging Hz	Casting Hz	Resonance Location
2223	2122	Main Blade, Leading Edge
3160	3060	Splitter Blade, Leading Edge
8605	8433	Blade Trailing Edges, Both Main and Splitter
17570	14569	Leading and Trailing Edges, Main Blades
18121	17301	Leading and Trailing Edges, All Blades

Figure 23. Hologram, Impeller Machined From Forging

Figure 24. Ho'ogram, Impeller Machined From Casting

The probable reason for the lower resonance frequency of the castings is that in processing the first lot no allowance was made for chemical machining subsequent to heat treatment, with the result that blade thicknesses are generally about 0.001 to 0.002 inch less than those of the forging. This variation has not constituted a problem in engine testing to date and should difficulties arise a remedy is at hand to correct the frequency of fundamental resonance by varying blade thickness.

Subsequent to the determination of mechanical, metallurgical, and resonance properties, the four machined impellers of the first casting lot were submitted to the Radial Engine Group for preliminary qualification consisting of proof spin testing, burst testing, and engine testing. Results, shown in Appendix B, show acceptable properties in both proof spinning and burst test, and in the initial stages of engine test.

The engine testing accumulated over 200 hours in endurance runs, including 1124 start/stop cycles. Engine performance has conformed to applicable standards and tear-down and inspection after 50 hours has indicated no problems with the impeller.

3

ECONOMIC ANALYSIS

Analysis of the economic effect of substituting castings for hogged out forgings for the Titan compressor impeller is complicated by the fact that the production process for the latter has been refined over the past several years, whereas castings have not yet been accepted for production. As an example, Solar was paying approximately $2200 per impeller in 1976, at the time this ManTech program was initiated. Current quotations for continuous production by hog-out in lots of 50 are $1740. The difference is attributed to the present constancy of production at the subcontractor, thereby eliminating set-up time and expenses in switching from one part to another; to the expertise gained in the learning process of extensive production; and, possibly, to the competition of cast impellers.

Conversely, present estimates for the cost of a finished part machined from a casting are somewhat higher than originally forecast. The casting itself has increased over $100 from the cost of those purchased in this program to an as-cast price of $672 in lots of 50. The increase is attributed to an increase in the price of titanium. The weight of the as-cast part, about four pounds plus risers, does not seem to justify this increase, however.

A more probable explanation for increased costs is the prohibition of welding and requirement for Grade A quality in the impeller vanes. Additionally, the $672 quotation includes mill annealing of the castings, which step is not really necessary since they are to be subsequently HIPed and heat treated. A savings of about $5 can be expected by elimination of the mill anneal.

HIPing costs are very much dependent upon quantities of castings processed. The basic charge quoted by IMT for one cycle (1650F/2 hours/15,000 psi) varies from $2600 for a 15.5 inch diameter by 56 inch long working chamber to $7000 for a 38 inch diameter by 100 inch long chamber, available later this year. The smaller chamber can accommodate between 50 and 80 castings the size of the Titan impeller and the cost, therefore is between $33 and $52 per part. The larger chamber will hold approximately 800 parts, bringing the cost below $10 each.

Machining cost quoted for the casting (by the subcontractor currently machining the forgings) is $250 each in lots of 50. This includes boring the hub, turning the vane diameters, polishing the blade tips, bead blasting, balancing and proof spinning, and reboring the hub to finish dimensions, all of which are also performed on the hogged out forging.

The same operations performed at Solar would be approximately $200 each in limited production or about $120 each in high volume.

PCC presently does not have the furnace capability to heat treat and age the castings after HIPing. Prototype castings were heat treated by Solar, necessitating that they be shipped from Portland, Oregon to Woburn, Massachusetts (IMT), back to Solar in San Diego for heat treatment and finally to Los Angeles for machining. Obviously a facility which offers combinations of heat treatment, machining and HIPing would have a substantial influence on the scheduling and shipping costs of the final machined impeller. The heat treatment, itself, can be conducted as a batch type operation and the cost will vary from a high of about $50 for a single casting to a low of about $10 for lots of 10 or more. The situation with aging after heat treatment is analogous and costs are expected to be about the same.

Adding the various costs involved in production of the cast and machined impellers the overall is seen to be about $900 less than the hogged out forging for equivalent high volume production in lots of 50:

	Cast and Machined	Forged and Machined
Casting	$667	Subcontract procurement $1740
HIPing	52	
Heat Treat	10	
Aging	10	
Machining	120	
	$859	

The greatest potential for further improvement in the economic status of cast and machined impellers is thought to lie in relaxation of welding prohibitions on the vanes and/or improvement of vane quality to obviate the need for welding. Improvement in overall quality and strength equivalent to forged properties may equilibrate the life cycle costs of the forged and cast impellers. Owing to lower tensile and fatigue properties of the casting it is possible that the service life could be shortened a proportionate amount. Engine testing to date has neither confirmed nor negated this possibility and the question remains open.

In summary, the cast and machined approach to compressor impeller fabrication offers substantial economic benefits over the conventional hogged out forging approach. There is some sacrifice in properties of the material but no compromise in compressor efficiency or reliability has been noted in limited service environment testing.

4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The following is a brief synopsis of the more significant conclusions identified in the evaluation of cast titanium alloy compressor impellers.

1. Average yield strength, tensile strength, and elongation of the HIPed and heat treated castings conform to respective 120 ksi, 130 ksi and 6% minima specified in requirements for current forgings. Projected population over a distribution of three standard deviations, however, indicates that as much as 33%, 10%, and 25%, respectively, will fall below requirements.

2. Fatigue strength of as-received or HIPed castings is 20 to 30 ksi reversed stress measured by a flexure test. This strength is consistent with earlier published values, but is below current forging values of ±60 ksi.

3. Partial solution heat treatment of the castings after HIPing is effective in dissolving grain boundary alpha phase, abetting fatigue strength. One method of effecting this treatment without undue distortion of blade sections is solution treatment for 1 to 2 hours at 1750°F, followed by rapid cooling, analogous to air blast, in an argon atmosphere. An increase in fatigue strength from ±30 ksi as cast to ±50 ksi after heat treatment has been achieved.

4. Vacuum aging improves both the yield and ultimate tensile strengths of the cast partial solution treated material and may have a further benefit in removal of trapped interstitial gases residual from the chemical machining treatment.

5. Cast Ti-6Al-4V impellers display excellent triaxial stress ductility in burst-spin testing to 300 percent of rated stress. Ductile, plastic deformation without formation of cracking at maximum speed, 106,000 rpm, was as much as 1.17 percent in the impeller bore, denoting a fail-safe design. This fact lends credence to the practice of proofing the impellers by spinning at 120 percent overspeed, 144 percent overstress, which test all four prototype impellers passed.

6. One casting, finish machined and installed in a Titan T62T-40 engine, has completed over 200 hours endurance running, including 1124 stop/start cycles without compromise to the engine efficiency or reliability.

7. Cast Ti-6Al-4V alloy parts exhibit corrosion and erosion resistance comparable to forgings of the same alloy.

8. HIPing is a necessary adjunct to the investment casting of titanium alloy parts intended for dynamic service, compensating for deficiencies in the process and for inadequacies of nondestructive inspection.

9. The effect of the HIP thermal cycle followed by slow furnace cooling is believed to promote growth of grain boundary alpha phase, to the detriment of high cycle fatigue life.

10. Of the foundries evaluated, Precision Castparts Corporation, Portland, Oregon, displayed the most consistent quality and was selected on this basis for production of the prototype impeller castings.

11. Substantial cost savings are available by the production of impellers from castings. The differential is very much a function of production quantities.

12. The program did not provide the property data base required for implementation. The data generated and the results are the basis for a continuing program. Implementation is being accomplished in a continuing Mantech effort.

4.2 RECOMMENDATIONS

1. Further improvement is needed in the casting process to improve the strength, ductility, and fatigue limits to the equivalent of forged material: (1) among the areas of preview are a more refined definition of the effect of heat treatment and aging on fatigue properties; (2) optimization of solution heat treating temperature, avoiding possible distortion of the vanes at elevated temperature or through cooling gradients, should be resolved; (3) the interaction of the solution heat treatment and aging needs further definition.

2. Additional improvement in elimination of vane-related defects may be possible by resizing the vane configuration to trap internal dross, porosity, and similar defects in an extended tip section which can be readily removed in the final machining process.

3. The large grain size of the castings, especially those produced by PCC, is thought to be at least partially responsible for reduced mechanical properties. It may be possible of refinement in two ways: (1) a center chill in the (eventually) bored hub of the casting will speed both the initial solidification rate and the cooling rate from HIP and heat treatment cycles; and (2) a second possibility is reduction in the preheating of the mold, again resulting in faster solidification and smaller grain size. The difficulty in this approach is to developing cold shuts on the surface or lack of fill in the vane sections due to too rapid chilling of the molten alloy as the mold is filling. Thicker vanes, subsequently reduced by chemical machining may be necessary.

4. The improvement in mechanical properties of cast Ti-6Al-4V alloy should be extended to other, more advanced alloys which will be required in higher temperature and/or higher stress engine applications. Assuming that these will be alpha-beta or super alpha alloys, as is probable, improvements can be expected from HIPing and heat treating procedures homologous to those applied to the Ti-6Al-4V castings. The technology of casting alternative alloys, and of applying optimized heat treatments needs to be developed, however.

5. Due to the nature of dynamic stresses in the vane section of impellers, surface finish is extremely important to avoid local intensification effects. The major factors which influence surface condition are the metal-mold reaction in casting, largely a function of foundry proprietary mold compositions and the chemical machining of the casting to remove oxygen-rich surface layers and to reduce blade thicknesses to print dimension. Subsurface porosity, if uncovered by the chemical machining, will not be healed in subsequent HIP operations and becomes a more serious problem. Conversely, thermal treatment, HIPing or heat treating, of castings which have had inadequate surface clean-up, can result in further diffusion of oxygen through the structure. Incomplete removal of the alpha ca- or oxygen enriched surface layer can, because of a then higher modulus, promote local stress concentration. A study should be conducted to determine a cost effective compromise between these alternatives.

APPENDIX A

DEMONSTRATION OF QUALIFICATION FEASIBILITY

DEMONSTRATION OF QUALIFICATION FEASIBILITY

Qualification feasibility testing of the cast compressor impeller is compromised of three main tasks:

1. Proof Spin Testing
2. Burst Spin Testing
3. Engine Operation Demonstration

PROOF SPIN TESTING

Four cast and finish machined impellers, P/N 160074-1, produced in accordance with the process control specification, Volume II, were spin tested in the facility shown in Figure A-1 to a speed of 73,500 rpm, held at that speed for one minute, and measured for dimensional growth. Operational speed of the Titan T62T-40 engine is approximately 61,250 rpm, so that 73,500 rpm represents 20 percent overspeed and 44 percent overstress conditions. Engineering drawing requirements require less than 0.001 inch growth in the bore, dimension "G", after spinning. Table A-1 shows negligible change, actually less than the accuracy of measurement method, (air gauge) in the bore, and minimal change at two locations on the major (blade tip) and minor (scallop) outside diameters. The noted dimensional changes are comparable to those noted in the equivalent forged impeller.

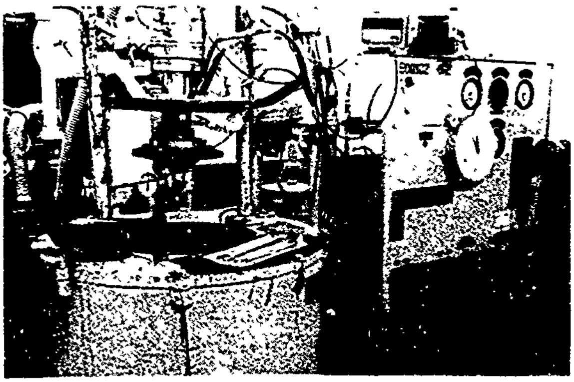


Figure A-1.

Spin Pit Facility

Table A-1

Cast Titanium Compressor Impeller Proof Spin Testing Results

Wheel Serial No.	Bore Dimension G*	Major OD**		Minor OD†	
		Station 1	Station 2	Station 3	Station 4
1054-0000A	0.77860 0.77856 (-0.00004)	6.2510 6.2523 (0.0013)	6.2505 6.2518 (0.0013)	5.730 5.730 (0.000)	5.736 5.736 (0.000)
1054-0002	0.77860 0.77867 (0.00007)	6.2535 6.2540 (0.0005)	6.2540 6.2540 (0.0000)	5.735 5.736 (0.001)	5.742 5.743 (0.001)
1054-0008	0.77830 0.77830 (0.00000)	6.2545 6.2547 (0.0002)	6.2545 6.2550 (0.0005)	5.732 5.733 (0.001)	5.736 5.737 (0.001)
1054-0005	0.77860	6.2540	6.2547	5.720	5.725

* Air Gauge Measurement
** Filar Micrometer Measurement
† Caliper Measurement

Note: Initial Diameter, inches
Final Diameter, Inches
Growth Diameter, Inches

BURST SPIN TESTING

One impeller, S/N 1054-0005, was rebalanced to 0.01 inch-ounce accuracy and was installed in the spin pit, Figure A-1. The impeller diameter was measured in six places at the initiation spinning and at increments of 5000 rpm to 100,000 rpm and 2000 rpm increments beyond that speed. A one minute dwell time was used at each speed increment. The test was abandoned after achieving a maximum speed of 106,000 rpm at which point growth of the rotor unbalanced the assembly, precluding further testing. Table A-2 is a compilation of changes in rotor dimension versus rotational speed. This data is also plotted in Figures A-2 through A-7. Operating speed of the engine is approximately 61,250 rpm and the test speeds have been referenced to this figure to calculate the overstress condition which the impeller experienced at each of the spin test speeds, a maximum of almost 300 percent at 106,000 rpm. The major outside diameter and bore diameter exhibited ductile growth at overspeed condition, but not until over 200 percent of rated, operating stress had been exceeded. The minor diameter at the tip of the blade leading edges began to experience a slight contraction at the same overspeed, overstress level as the growth of the back side and bore of the impeller imposed a bending moment on the front face. Figures A-8 through A-12 show views of the impeller, before and after burst

spin testing, showing the development of strain lines and ductile crack patterns on the back face. The ability of the cast titanium alloy to relieve stresses by plastic deformation in triaxial stress fields is demonstrated by these tests and the yield strength of the material is adequate to provide a wide margin of overspeed tolerance. In summary, the ductility and strength of the material are such as to provide adequate burst speed for the impeller.

ENGINE OPERATION DEMONSTRATION

The third step of qualification is engine operation. Limited testing was conducted during this MM&T to demonstrate feasibility of this approach. One of the four cast impellers, S/N 1054-0002, was installed in a Titan T62T-40 test engine for test essentially as described in the following Engine Qualification Test Procedure. The demonstration included 60 hours service time and 200 stop/start cycles without difficulty. Performance conformed to all requirements of the engine; and teardown and inspection at 50 hours disclosed no discrepancies with the impeller. Testing was continued with the objective of ultimate qualification of the cast titanium impeller, produced to requirements of Volume II, Process Control Documents, as an alternate to the presently available forged and machined compressor impellers.

Table A-2

Burst Spin Test

Impeller Speed (rpm)	Percent Rated Operating Stress	Major OD Diameter (in.)		Minor OD Diameter (in.)		Bore Diameter (in.)	
		Sta. 0-180	Sta. 90-270	Sta. 0-180	Sta. 90-270	Sta. 0-180	Sta. 90-270
Initial	-	6.2545	6.2545	4.2784	4.2782	0.7785	0.7784
70,000	130.6	6.2547	6.2546	4.2784	4.2782	0.7785	0.7784
75,000	149.9	6.2547	6.2546	4.2784	4.2782	0.7785	0.7784
80,000	170.6	6.2547	6.2546	4.2784	4.2782	0.7785	0.7785
85,000	192.6	6.2547	6.2546	4.2784	4.2782	0.7785	0.7785
90,000	215.9	6.2550	6.2549	4.2764	4.2782	0.7787	0.7787
95,000	240.6	6.2558	6.2556	4.2764	4.2782	0.7789	0.7788
100,000	266.5	6.2565	6.2563	4.2784	4.2782	0.7789	0.7788
102,000	277.3	6.2574	6.2573	4.2784	4.2782	0.7810	0.7818
104,000	288.3	6.2591	6.2588	4.2580	4.2779	0.7835	0.7831
106,000	299.5	6.2619	6.2621	4.2779	4.2778	0.7850	0.7875

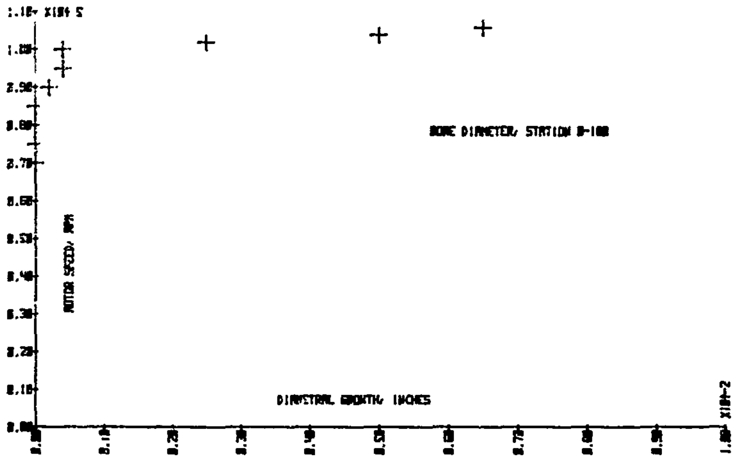


Figure A-2. Overspeed Burst Test - Diametral Growth of Cast Ti-6Al-4V Impeller Bore

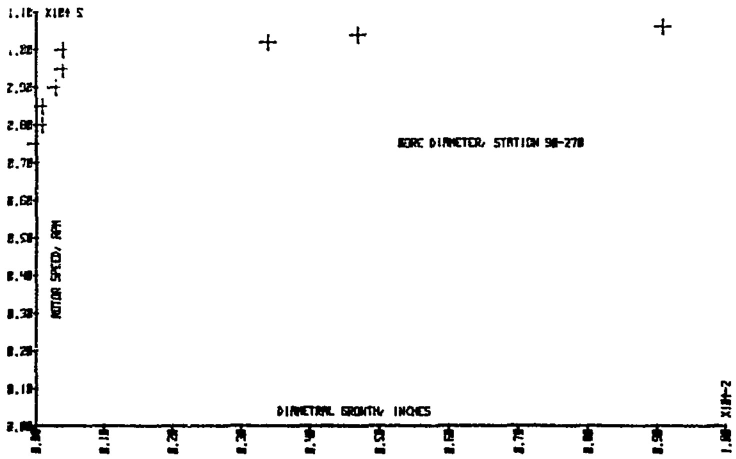


Figure A-3. Overspeed Burst Test - Diametral Growth of Cast Ti-6Al-4V Impeller Bore

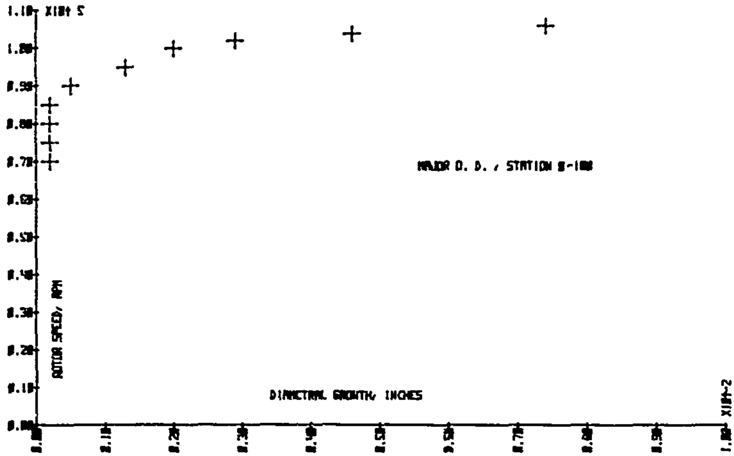


Figure A-4. Overspeed Burst Test - Diametral Growth of Cast Ti-6Al-4V Impeller Vane Trailing Edges

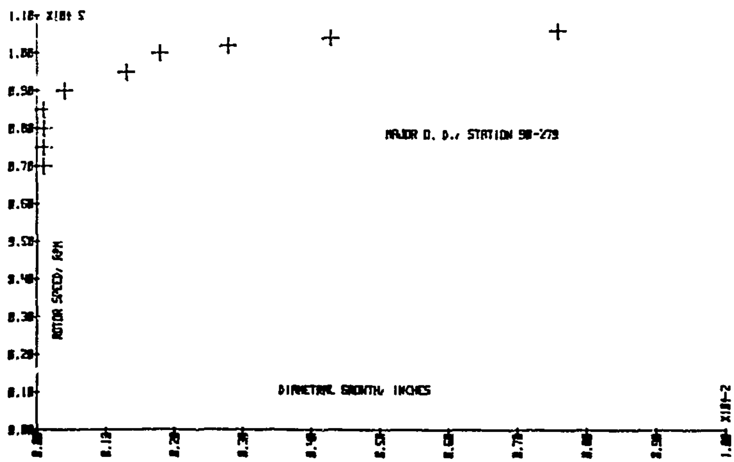


Figure A-5. Overspeed Burst Test - Diametral Growth of Cast Ti-6Al-4V Impeller Vane Trailing Edges

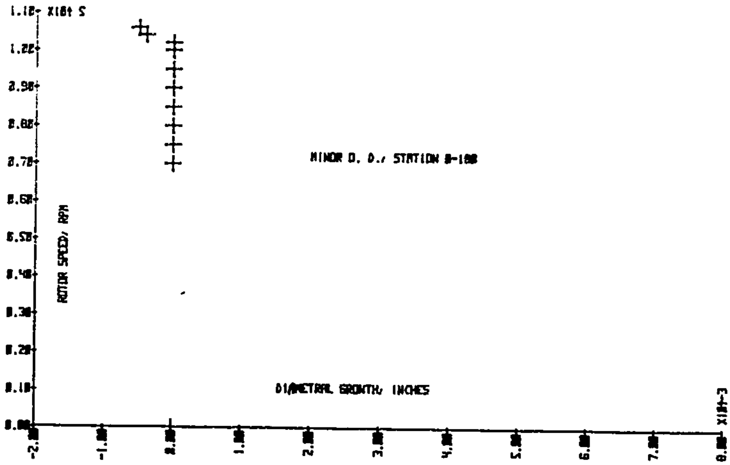


Figure A-6. Overspeed Burst Test - Diametral Shrinkage of Cast Ti-6Al-4V Impeller Leading Edges

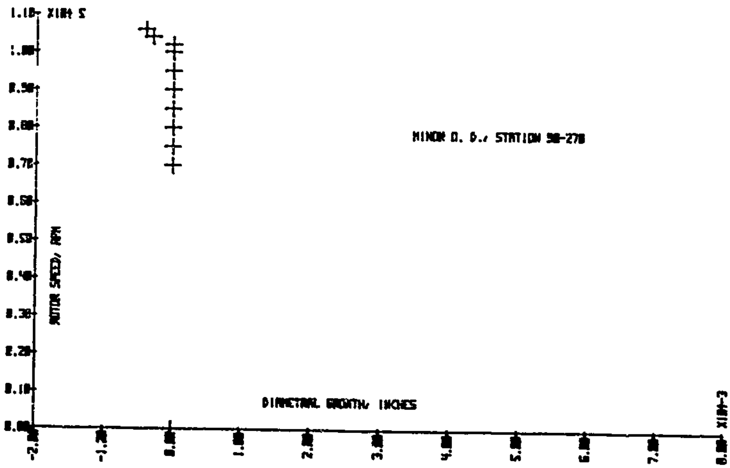


Figure A-7. Overspeed Burst Test - Diametral Shrinkage of Cast Ti-6Al-4V Impeller Leading Edges

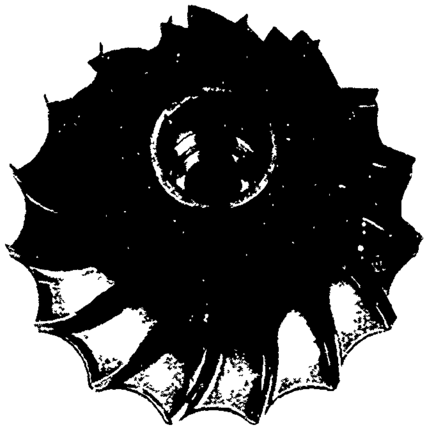


Figure A-8. Front Face of Finish Machined and Balanced Impeller Prior to Burst Test (#78-3922)

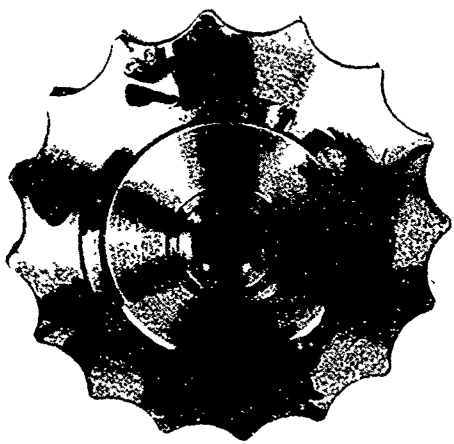


Figure A-9. Back Face of Finish Machined and Balanced Impeller Prior to Burst Test (#78-3923)

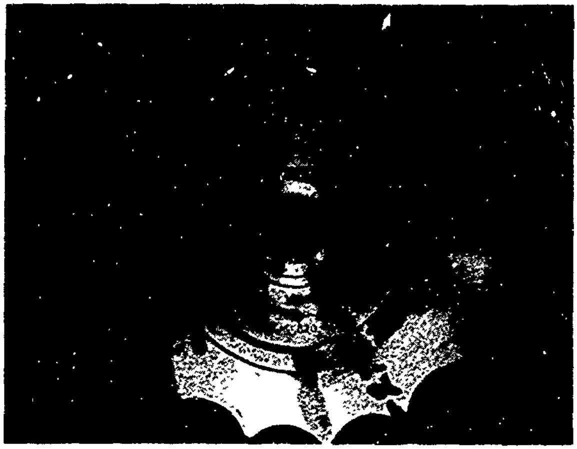


Figure A-10. Strain Lines in Back Face of Impeller After Final 106,000 rpm Spin (#78-4016)

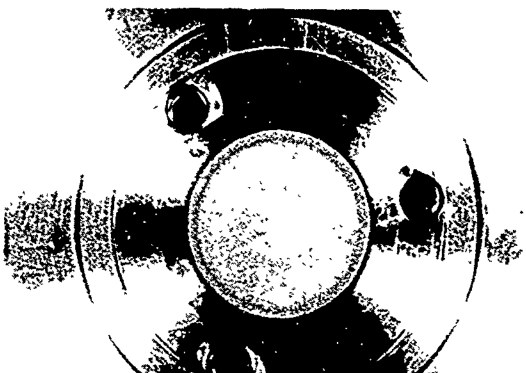


Figure A-11. Localized Strain Lines at Dowel Pin Holes Adjacent to Bore (#78-4015)

Figure A-12. Magnified View of Dowel Pin Holes Showing Strain Lines and Ductile Cracking (#78-4014)

APPENDIX B

ENGINE QUALIFICATION TEST RESULTS

ENGINE QUALIFICATION TEST RESULTS

B.1 INTRODUCTION

During June 1976 Solar Turbines International was awarded a contract by the U.S. Army Materials and Mechanics Research Center (AMMRC) to evaluate the feasibility of a Cast Titanium Alloy Compressor Wheel for use as a substitute for the more expensive, machined, T62T-40 compressor. Based upon the encouraging results of limited (60 hour, 200 start/stop cycles) testing it was decided to continue the engine tests on a more extensive basis. This section presents the results of the engine tests conducted by Solar Turbines International.

The engine utilized for the test was a Titan, T62T-40C Auxiliary Power Unit, S/N-775001. The engine is a civilian version of the T62T-40-1 and is capable of producing up to 72 ppm of bleed air at a pressure of 36 psig with zero shaft load; or 40 shp and 40 ppm of bleed air simultaneously at standard sea level conditions.

The test was conducted under sea level conditions in Solar's Engine Development and Test Facility and consisted of 200 hours of endurance plus a total of 1124 starts. The endurance test was run simultaneously with a development bearing program as a cost/time reduction measure.

B.2 SUMMARY

The test engine started, performed well, and from all visual indications the cast titanium compressor wheel was in good condition at the completion of the test period. Due to problems with the rotor bearings selected for the test, there were more than the scheduled number of teardowns and inspections. The compressor was inspected visually each time and by Zyglo on at least one occasion. The wheel showed no new indications until the final Zyglo results (after 200 hours and 1124 starts) were reviewed. At that time an area at the fillet of one of the "short" blades showed an indication of porosity or surface crack. The part was returned to the Research Department for an investigation. Evaluation of the indication was not made by the Test Department.

Forty-four starts were made and recorded in addition to the scheduled 1980. There were no aborted starts or failures to light and accelerate in the 1124 attempts.

B.3 CONCLUSIONS AND RECOMMENDATIONS

It can be concluded from the results of the qualification tests that the cast titanium compressor, Solar P/N 105770-5, has the structural reliability to be considered for further development as a replacement for the standard titanium part S/N 105770-1. It is recommended that a part remain in the test engine and be run through further tests including environmental testing with inlet temperatures ranging from -65°F to +160°F.

B.4 DESCRIPTION OF TEST ARTICLE

The test engine was a T62T-40C basically built to Solar Drawing #160181-300 with minor modifications that classified the unit as a test laboratory "slave" engine. The engine had the following modifications:

1. MRC Rotor Thrust Bearing, S/N R030, MRC P/N 9203-UD-3 (200 hr)

2. Turbine Nozzle, Solar P/N 113089-200, Rev. H, No. S/N (100 hr)

3. Turbine Nozzle, Solar P/N 113089-100, Rev. F, S/N 6382-0012 (100 hr)

4. MRC Rotor Support Bearing, S/N 2088 (100 hr)

5. New Departure Rotor Support Bearing, S/N 78M201, (50 hr)

6. MRC Rotor Thrust Bearing, S/N 2087 (0.1 hr)

7. New Departure Rotor Thrust Bearing, S/N 78L23 (10 hr)

8. New Departure Rotor Thrust Bearing , S/N 78L82 (40 hr)

9. South Bend Controls Main Fuel Solenoid, S/N 102 (200 hr)

10. Anti-Surge Valve, P/N 160360-4 substituted for standard P/N 116231-4 (200 hr)

B.5 DESCRIPTION OF INSTALLATION

All testing was performed in the Solar Radial Engine Development Test Facility, San Diego, California. Installation was as described in the following paragraphs and shown in Figures B-1 and B-2.

B.5.1 Air Supply

Air was drawn from the cell at prevailing ambient temperatures through a standard inlet screen during the endurance testing. During the performance calibration air was drawn through a 6.0 in. Venturi vented to the outside atmosphere.

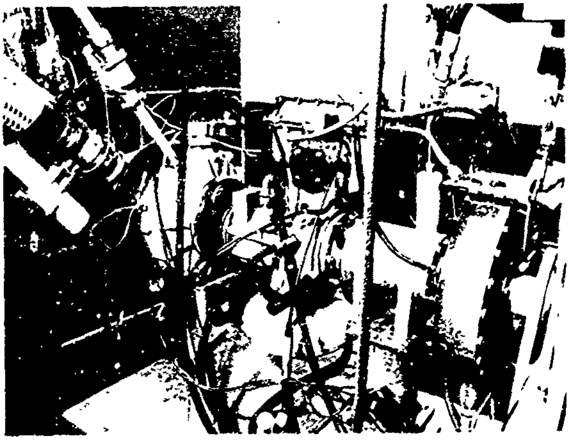


Figure B-1. Test Engine S/N 775001 Mounted for 200 hour Endurance Test (Cell 31-2, Bldg. #31, July 1979) (#79-3360)

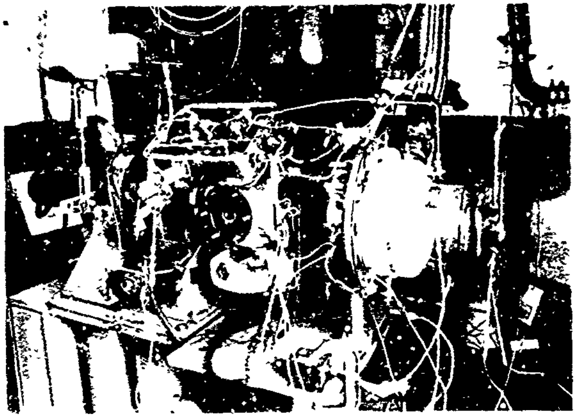


Figure B-2. Test Engine S/N 775001 Mounted for 200 hour Endurance (Cell 31-2, Bldg. #31, July 1979) (#79-3361)

B.5.2 Fuel

Fuel conforming to MIL-T-5624, JP4 was used for the first 100 hours of endurance and fuel conforming to MIL-T-5624, JP5 was used for the second 100 hours. The change was necessitated by changes in other engine components which were being tested simultaneously.

B.5.3 Exhaust Gas Disposal

Exhaust gas was ducted from the cell.

B.5.4 Bleed Air System

Engine bleed air was exhausted through a load modulating valve (STD engine valve) and a flow measuring device consisting of a 2.59 inch orifice in a 4.0 inch run designed to ASME standards. Load was simulated by a remote control 3-inch ball valve located "downstream" of the previously mentioned system.

B.5.5 APU Mounting

The unit was directly attached, at the output drive pad, to a viscous shear water dynamometer and with a single point resilient mount attached at the underside of the inlet housing.

B.5.6 Shaft Power Absorption

A viscous shear water dynamometer was directly attached to the main output drive pad. A Chatillon scale with a calibrated lever arm was used to read horsepower directly.

B.5.7 Start System

APU starting was accomplished using a Delco Model 50282 electrtic, 24 volt dc, starter driving through the dynamometer.

B.5.8 Electrical System

Facility power for starting was supplied from a 24 volt battery system with an ac powered charging system. Control power was supplied by a 24 volt power supply.

B.5.9 Lubricating Oil

Lubricating oil conforming to MIL-L-7808 was utilized for the first 100 hours of endurance and MIL-L-23699 was used for the second 100 hours.

B.6 INSTRUMENTATION

Prior to the initiation of testing, the instrumentation was inspected and verified that all instruments were within the current calibration period. For the engine performance evaluation tests, instrumentation was arranged as shown in Table B-1. For the endurance poriton of the test, instrumentation was reduced to the parameters shown in Table B-2. The range and accuracy of each measurement are shown on the respective tables.

B.7 METHOD OF TEST

B.7.1 Preliminary Engine Test

The test unit was installed in a standard Titan, sea level test chamber as described by Section 5. Instrumentation was attached as listed in Section 6.

B.7.1.1 Preliminary Run #1

With the fuel and ignition systems disconnected, two engine cranking runs of approximately 10 seconds duration were made. Notation was made of oil pressure indicatiors and unusual noises during rundown.

B.7.1.2 Preliminary Run #2

With the fuel and ignition systems reconnected, two successive 50% starts were made. When engine speed reached 50%, the engine was shut down and notation was again made of unusual engine noises and vibration indications.

B.7.1.3 Prelimimary Run #3

The engine was started, allowed to accelerate to 100% speed, and run at "no load" conditions for 10 minutes. During the 10-minute time period, a data point was taken to check the operation of all instrumentation. The engine was shut down and the run-down was observed for unusual noises.

B.7.1.4 Preliminary Run-Overspeed

With the engine shutdown, an oscillator was attached to the magnetic pickup lead. Using the false signal input, the control box was electronically sequenced to operating speed. The input frequency was increased until an overspeed indication was observed. The exact frequency was recorded.

Table B-1

Engine Performance Calibration Measurement Requirements

Description	QT.	Measurement Device	Range	Accuracy
Venturi Throat Static Pressure	1	Water Manometer	0-100"	± .05" H_2O
Venturi Inlet Temperature	1	Doric TC Thermocouple Indicator*	-328 to +1712°F	± 1°F
Compressor Air Inlet Temperature	3	Doric TC Thermocouple Indicator*	-328 to +1712°F	± 1°F
Inlet Muff Static Pressure	1	Water Manometer	0-50"	± .50" H_2O
Compressor Discharge Pressure	1	Precision Test Gauge**	0-100 psig	± .25% FS
Bleed Orifice Temperature	1	Doric IC Thermocouple Indicator	-328 to +1712°F	± 1°F
Bleed Orifice Static Pressure	1	Precision Test Gauge	0-100 psig	± .25% FS
Bleed Orifice Delta Pressure	1	Water Manometer	0-100 inches	± .05" H_2O
Fuel Flow, Weight	1	Turbine Flowmeter	20-260 pph	± 1 pph
Exhaust Gas Temperature	6	Doric CA Thermocouple Indicator*	-200°-2552°F	± 1½°F below 0°F & ± 1°F above 0°F
Exhaust Gas Static Pressure	1	Water Manometer	0-100" H_2O	± .05" H_2O
Engine Speed	1	Magnetic Pickup to Electronic Digital Counter	0-9999 Hz	± Hz. per count per
Dynamometer Load	1	Chatillon Dynamometer Scale	0-100 lb.	± ½ lb.
Vibration, Engine	1	Into MB Electronics M6 Meter	g's .1 to 10 10 to 100	5% FS
Vibration, Reduction, & Accessory Drive	1	Into MB Electronics M6 Motor	g's .1 to 10 10 to 100	5% FS
Fuel Pressure (Supply)	1	Bourdon Tube Gauge	-30 to +30 psi	± .5 psi
Oil Pressure	1	Bourdon Tube Gauge	0-60 psig	± .5 psi
Oil Sump Temperature	1	Doric IC Thermocouple Indicator	-328°F to +1712°F	± 1°F
Ambient Air Pressure	1	Mercury Barometer	25.5 to 32.7"Hg	± .01" Hg
Acceleration Time	1	Electrical Timer	0-9999.9 sec.	± .1 sec. in 100

* Self Balancing potentiometer
** Precision bourdon tube gauge
*** FS = full scale indication

Table B-2

Endurance Test Measurement Requirements

Description	Qty	Measurement Device	Range	Accuracy
MANUAL READOUTS				
Ambient Air Pressure	1	Hg Barometer	25.5 to 32.7" Hg	± .01" Hg
Compressor Inlet Temperature	1	Doric IC Thermocouple Indicator	-328 to 1712°F	± 1°F
Bleed Air Temperature	1	Doric IC Thermocouple Indicator	-328 to 1712°F	± 1°F
Oil Sump Temperature	1	Doric IC Thermocouple Indicator	-328 to 1712°F	± 1°F
Exhaust Gas Temperature	1	Doric CA Thermocouple Indicator	-208 to 2552°F	± 1°F
Engine Speed	1	Magnetic Pickup & Electronic Digital Counter	0-9999 Hz	± 1 count per perio
Dynamometer Load	1	Chatillon Dynamometer Scale	0-100 lbs.	± 1/2 lb.
Fuel Flow, Weight	1	Turbine Flow Meter	20-260 pph	± 1 pph
Bleed Orifice Delta [illegible]	[illegible]			
Bleed Orifice Static Pressure	1	Precision Test Gauge	0-100 psig	± .25% FS*
Compressor Discharge Pressure	1	Precision Test Gauge	0-100 psig	± .25% FS

* FS = Full Scale Reading

B.7.1.5 Preliminary Run-Overtemperature

With the engine shut down, an oscillator was connected to the magnetic pickup lead and a millivolt power supply was connected to the exhaust gas temperature thermocouple lead. Using the oscillator the control box was electronically sequenced to 100% operating speed. The output of the millivolt power supply was increased until an overtemperature indication was observed. The exact value of the millivolt signal was recorded along with the equivalent F° reading.

B.7.2 Performance Calibration Test

Following the successful completion of the tests listed under Section B.7.1, the test engine was set up with instrumentation as listed in Table B-1. A 28 VDC motor was attached to the engine generator speed screw so that the engine speed could be adjusted to create 59°F standard day conditions.

A performance calibration was run and data was recorded at each of the following load conditions with engine speed adjusted to 59°F standard day conditions:

- No load
- No bleed load + 20 shaft horsepower
- No bleed load + 40 shaft horsepower
- No bleed load + 60 shaft horsepower
- No bleed load + 90 shaft horsepower
- No bleed load + 90 shaft horsepower
- No shaft horsepower + bleed flow to obtain an EGT of 750°F
- No shaft horsepower + bleed flow to obtain an EGT of 875°F
- No shaft horsepower + bleed flow to obtain an EGT of 1000°F
- No shaft horsepower + bleed flow to obtain an EGT of 1100°F
- No shaft horsepower + bleed flow to obtain an EGT of 1200°F
- 40 shaft horsepower + bleed flow to obtain an EGT of 1200°F

The data from the calibration was reviewed and the values compared with the model specification performance.

B.7.3 Endurance

An endurance test consisting of 200 hours of cyclic load running and 1124 starts was conducted in accordance with the schedule of Table B-3. Instrumentation was attached as listed in Table B-2.

B.7.4 Post-Test Performance Calibration Test

Following the completion of the endurance test, the engine was set up as described by Section B.7.2 and a second calibration was run with data recorded at similar load conditions.

Table B-3

Endurance Test Sequence

Sec.	Time (Min.)	Engine Condition	Engine HP	Engine Bleed (PPM)	Operating Time (Min.)
A	5 5 50 -	Start and run at max shaft HP output Run at no load Run at normal rated output Shut down for 5 minutes	60 0 20 -	0* 0 60 -	5 10 60 -
B	5 5 50 -	Start and run at max shaft HP output Run at no load Run at 75% rated output Shut down for 5 minutes	60 0 15 -	0* 0 45 -	65 70 120 -
C	5 5 50 -	Start and run at max shaft HP output Run at no load Run at rated output Shut down for 5 minutes	60 0 20 -	0* 0 60 -	125 130 180 -
D	5 5 50 -	Start and run at max shaft HP output Run at no load Run at 50% rated output Shut down for 5 minutes	60 0 10 -	0* 0 30 -	185 190 240 -
E	5 5 50 -	Start and run at max shaft HP output Run at no load Run at rated output Shut down for 5 minutes	60 0 20 -	0* 0 60 -	245 250 300 -
F	5 5 50 -	Start and run at max shaft HP output Run at no load Run at 25% rated output Shut down for 5 minutes	60 0 5 -	0* 0 15 -	305 310 360 -
G	5	Start and run at max shaft HP output	60	0*	600

Note: Repeat Section "G" 48 times - delay 2 minutes between runs.
Repeat cycle 20 times.

Totals: (20 cycles)

1080 starts and 200 hours operating time.
20 starts preceded by a minimum two hour shutdown
30 starts preceded by a 2 hour shutdown will be accomplishment at completion of endurance run.

* Use bleed as required to prevent compressor surge.
* or 1200°F exhaust gas temperature whichever is lower.

20

Following the calibration, the data was reviewed and calculations performed. The results were plotted versus the original calibration results, as shown in Figure B-3.

B.7.5 Post-Test Inspection

The test engine was removed from the test stand and returned to the assembly area for a teardown and inspection. All major parts were given a "dirty" inspection and photographed. Rotor parts were inspected for cracks. All results are displayed in this report.

B.8 RESULTS AND DISCUSSION

The cast titanium compressor test was combined with an internal bearing development program. This program, and the problems resulting from it, resulted in an additional 70 hours of engine operation with the cast wheel and several additional teardowns. These component changes and teardowns are documented in the report. Problems with the bearing system were due to the experimental nature of the bearings and with discrepant parts, and were totally unrelated to the compressor wheel configuration.

The engine was returned to the assembly area four times for bearing changes and inspections. Each time, the compressor and other major engine parts were found to be in good condition and were reused. There were no other part substitutions other than the bearings and associated hardware. During one teardown, it was necessary to replace the rotor shaft that was damaged by an overheated bearing.

The final teardown and inspection of the test unit revealed that all major engine parts were in good condition. The impeller is seen in Figure B-4. There were, however, Zyglo indications on the fillet of one of the short blades at the hub of the compressor. To the untrained eye, without the benefit of extra chemical treatment or a magnifying lens, the indication resembled porosity. The part was returned to the Research Department for more complete analysis. The results of a microscopic examination indicated an inperfection in the casting surface resulting from a break in the investment and consequent surface contamination. The imperfection is seen in Figure B-5.

With regard to engine performance, the cast compressor performed without problems. A plot of engine performance before and after the endurance is shown as Figure B-3. There was essentially no engine performance deterioration. Performance of the engine was, however, marginal for a T62T-40C, but this was in no way attributable to the cast impeller.

It is recommended that the cast compressor be subjected to further testing including a series of environmental tests. It is not recommended at this time that the compressor be used in production units until a sound statistical basis of reliability is developed for a larger propulation. Qualification of a cast titanium alloy impeller is continuing under another program.

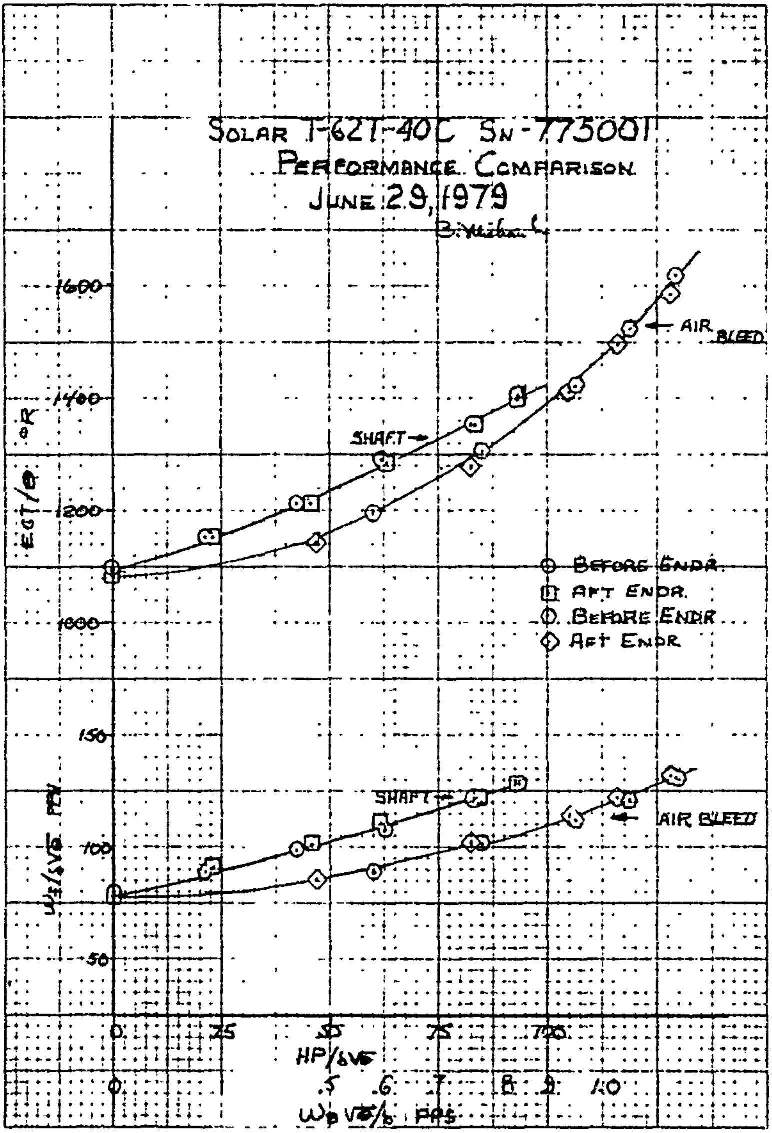


Figure B-3. Post-Test Performance Calibration

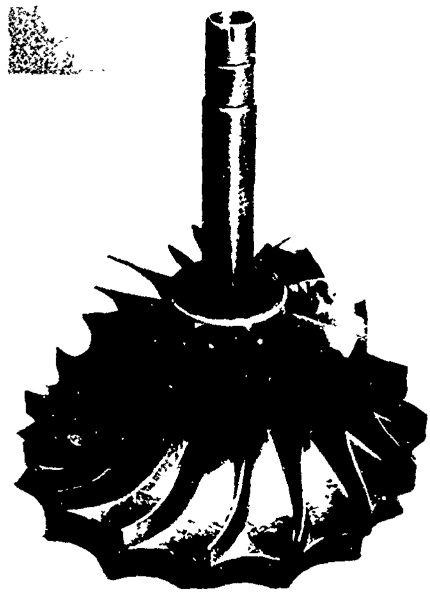


Figure B-4. Compressor Wheel, P/N 160074-1, S/N 1054-0002. From T62T-40C S/N 775001, Following a 200 Hour Endurance, July 1979. Total Hours Approximately 283. (#79-3560)

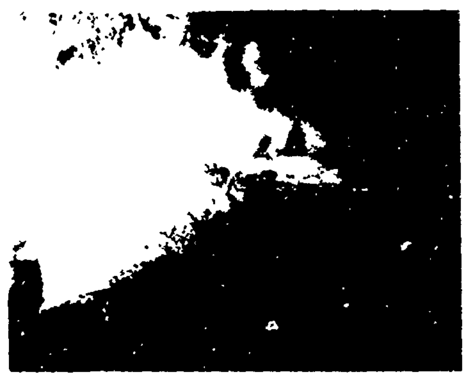


Figure B-5. Photomacrograph of Irregularity on Compressor Vane, Leading Edge, Near Hub, Identified as Resulting From a Break in the Shell Mold.

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EVALUATION OF CAST TITANIUM ALLOY COMPRESSOR
COMPONENTS - VOLUME I - Alvin N. Hammer
Solar Turbines Incorporated, 2200 Pacific Hwy,
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Fatigue Strength
Heat Treatment
Auxiliary Power Units

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